

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Delamination modelling of 3D woven composites for dynamic loadings applications

Rui Jorge de Sousa Gonçalves

Master Dissertation

FEUP Supervisor: Prof. Carolina Furtado Silva

ISAE-Supaero Supervisor: Frédéric Lachaud



**Masters in mechanical engineering
Aeronautical and Vehicle Structures**

06 October 2023

“The only person you are destined to become is the person you decide to be.”

Resumo

Os materiais compósitos tridimensionais têm vindo a ser cada vez mais utilizados na indústria aeronáutica. Devido à sua complexidade e ao seu comportamento anisotrópico, é necessária uma melhor compreensão da sua resposta a várias solicitações e taxas de carregamento. Um dos comportamentos que carece de investigação é a delaminação induzida por impactos de baixa velocidade, que produzem principalmente delaminação de Modo II (cisalhamento), que é difícil de detetar. Com a introdução da velocidade nos ensaios dinâmicos (para simular impactos de baixa velocidade), o efeito da taxa de deformação é uma nova variável introduzida para a modelação da delaminação dos compósitos tecidos 3D.

Este trabalho centrou-se nos ensaios experimentais e, subsequentemente, na modelação numérica dos ensaios de Modo II. O ensaio Thick Adherend Shear Test (TAST) foi utilizado para obter a resistência ao cisalhamento interlaminar, enquanto que para a resistência à fratura por delaminação (DFT) foram utilizados o ensaio Four End Notched Flexure (4ENF) para o modo II puro e o ensaio Cracked Lap Shear (CLS) para o comportamento de modo misto.

Apenas os ensaios estáticos puderam ser realizados, e as propriedades resultantes foram introduzidas num Modelo de Zona Coesiva (CZM), utilizando elementos e superfícies coesivas, e também uma Técnica de Fecho de Fendas Virtual (VCCT) para obter a comparação numérica com os resultados dos ensaios. Os resultados experimentais obtiveram um DFT no Modo II que foi exceccionalmente elevado, resultando numa Comprimento da Zona Coesiva (CZL) irrealisticamente grande, que tenta representar a Zona de Processo de Fratura (FPZ) do material. Para além disso, a separação da interface fibra/matriz foi identificada como o modo de falha, tal como esperado para um teste estático.

Para reduzir a CZL, foi introduzido um novo material de utilizador coesivo (UMAT) utilizando uma lei trapezoidal que alterou a dimensão do patamar de acordo com o comportamento do modo misto. Isto conduz a uma lei triangular aparente no Modo I e a uma lei trapezoidal para o resto do comportamento. O UMAT apresentou melhores resultados do que os outros modelos, especialmente no modelo o tests CLS, reduzindo a FPZ como pretendido. Para quando forem efectuados os ensaios dinâmicos, o UMAT foi também preparado para introduzir os efeitos da taxa de deformação no CZM.

Abstract

Three-Dimensional woven have become increasingly used in the aeronautical industry. Due to their complexity and anisotropic behaviour, it is required a better understanding of their response to various loadings and loading rates. One of the behaviours that is lacking in research is delamination induced by low velocity impacts, which produce mainly Mode II (shear) delamination, which is hard to detect. With the introduction of velocity in dynamic tests (to simulate low velocity impacts), strain rate effect is a new variable introduced for the delamination modelling of the 3D woven composites.

This work focused on the experimental testing and subsequently numerical modelling of Mode II testing. The Thick Adherend Shear Test (TAST) was used to acquire the interlaminar shear strength, while for the delamination fracture toughness (DFT) the Four End Notched Flexure (4ENF) test for pure Mode II and the Cracked Lap Shear (CLS) for mixed mode behaviour where utilised.

Only the static tests were able to be performed, and the resulting properties were inputted in a Cohesive Zone Model (CZM), using cohesive elements and surfaces, and a Virtual Crack Closure Technique (VCCT) for attaining the numerical comparison to the tests results. The experimental results obtained a DFT in Mode II that was exceptionally high, resulting in an unrealistically large Cohesive Zone Length (CZL), that tries to represent the Fracture Process Zone (FPZ) of the material. Furthermore, fiber/matrix interface debonding was identified as the failure mode, as expected for a static test.

To reduce the CZL, a new cohesive User Material (UMAT) was introduced using a trapezoidal law which changed the size of the plateau according to the mixed mode behaviour. This leads to a perceived triangle law in Mode I, and a trapezoidal law for the rest of the behaviour. The UMAT showed better results than the other models, especially on the CLS test model, reducing the FPZ as intended. For when the dynamic tests are performed, the UMAT was also prepared to introduce the strain rate effects within the CZM.

Acknowledgements

First and foremost, I would like to thank my supervisors, Mr. Frédéric Lachaud, Mr. Éric Paroissien, Mr. Sylvain Mousillat, and Ms. Carolina Silva, without whom this internship would not have been possible. Their excellent scientific skills and attention to detail guaranteed that the thesis progressed successfully.

I would also like to thank the members of the DMSM laboratory, Xavier Foulquier, Matthieu Hospital, Thierry Martin, Frédéric Bontemps, and Véronique Godivier, for their availability and participation in the project, to which they contributed in the experimental part, specimen cutting, manufacturing, design of an assembly, and microscopic analysis.

I would also like to express my gratitude to my university, FEUP, which granted me the opportunity to integrate the ERASMUS+ Programme for internships to finalise my Master's. Without this programme's financial help, it would be very hard to initiate this challenge.

Additionally, I want to appreciate the time and help I received throughout the internship from my colleagues, Guilherme Coelho, Sergio Pérez, and Pedro Gallego, with whom I spent most of my time in and out of the laboratory. Guilherme, especially, thank you for always being a companion to travel and experience Occitanie.

Finally, I am extremely grateful for having the best person to always be there for me emotionally and mentally. Even with distance, we were able to endure and have experiences together. Without your support, perseverance, and patience, I wouldn't be able to take up this adventure. With love, thank you, Joana.

Contents

1	INTRODUCTION	1
1.1	OBJECTIVES OF THE PROJECT	2
1.2	STRUCTURE OF THE THESIS	3
2	STATE OF ART	5
2.1	COMPOSITE MATERIALS	5
2.1.1	WOVEN ARCHITECTURES	6
2.1.2	FAILURE MODES OF COMPOSITES	8
2.2	STATIC INTERLAMINAR FRACTURE TESTING	8
2.2.1	DELAMINATION INITIATION CRITERIA	9
2.2.2	DELAMINATION FRACTURE TOUGHNESS (DFT)	10
2.2.3	ANALYTICAL METHODS FOR THE MODE II DFT	13
2.2.4	DFT EXPERIMENTAL CALCULATION	15
2.2.5	DELAMINATION MODE II EXPERIMENTAL TESTS	16
2.3	DYNAMIC CONSIDERATIONS	20
2.3.1	EXPERIMENTAL MACHINES	22
2.3.2	STRAIN RATE (SR) EFFECT REVIEW	23
2.4	DELAMINATION SIMULATION	27
2.4.1	STATIC MODELS	27
2.4.2	DYNAMIC CZM FOR STRAIN RATE EFFECTS	34
3	TEST CAMPAIGN	37
3.1	MATERIALS	37
3.2	TEST MATRIX	37
3.2.1	TEST SPEED AND TEST TYPES	37
3.2.2	INTERLAMINAR SHEAR STRENGTH TESTS	38
3.2.3	CRACK RESISTANCE CURVE TESTS	39
3.2.4	DRM AND SIZING OF THE DELAMINATION TESTS	41
3.3	SPECIMENS CUTTING AND PREPARATION	46
3.4	EXPERIMENTAL PROCEDURE	47
3.4.1	DIC MEASUREMENTS AND POSTPROCESSING	48
3.4.2	DIC PROJECTION ERRORS	51
3.5	STATIC RESULTS	52
3.5.1	TAST WARP DIRECTION	52
3.5.2	TAST WEFT DIRECTION	56
3.5.3	SHORT 4ENF SPECIMEN	59
3.5.4	LONG 4ENF SPECIMEN	60
3.5.5	CLS	64
3.6	COHESIVE MATERIAL PROPRIETIES FOR NUMERICAL MODELS	68

4	USER MATERIAL	71
4.1	UMAT FORMULATION	71
4.1.1	UMAT VALIDATION	75
4.2	DYNAMIC POSSIBILITIES	78
4.2.1	UMAT SIMPLE STRAIN RATE FORMULATION	78
4.2.2	UMAT COMPLEX STRAIN RATE FORMULATION	80
5	NUMERICAL AND COMPARISON	83
5.1	NUMERICAL METHODOLOGY	83
5.2	STATIC TESTS	84
5.2.1	MODELS CREATION 4ENF	84
5.2.2	VISCOSITY CONVERGENCE METHOD FOR UMAT	89
5.3	STATIC RESULTS	90
5.3.1	TAST WARP DIRECTION	90
5.3.2	TAST WEFT DIRECTION	92
5.3.3	SHORT 4ENF	94
5.3.4	LONG 4ENF	96
5.3.5	CLS	99
5.3.6	ELS	102
6	CONCLUSIONS	103
	ANNEX A. CATIA DRAWINGS OF THE SPECIMENS	I
A.1.	TAST SPECIMEN	II
A.2.	LONG 4ENF SPECIMEN	III
A.3.	CLS SPECIMEN	IV
A.4.	ELS SPECIMEN	V
	ANNEX B. PYTHON AND MATLAB EXAMPLES	VII
B.1.	4ENF UMAT MODEL CREATION	VII
B.2.	4ENF UMAT ODB READER	XIX
B.3.	EXPERIMENTAL 4ENF MATLAB	XXI
B.4.	TAST ODB READER	XXXI
B.5.	NUMERICAL TAST MATLAB	XXXV
	ANNEX C. ELS STABILITY CHECK AND RESULTS	XLI
	ANNEX D. NEW UMAT FORMULATION	XLVII
D.1.	FORTRAN CODE	L
	ANNEX E. SHORT 4ENF LOADING VARIANCE	LV
	REFERENCES	LVII

Índice de Figuras

Figure 1 – Composite laminate directions and planes.....	6
Figure 2 – 2D woven fabric architectures.	6
Figure 3 – Delamination modes.	8
Figure 4 – Thick Adherend Shear Test (TAST) to simulate crack initiation.	10
Figure 5 – Fracture Process Zone illustrated for delamination in Mode I and Mode II.	11
Figure 6 – ENF standard specimen.	13
Figure 7 – Illustration of the area method.	15
Figure 8 – ONF standard specimen.	17
Figure 9 – 4ENF standard specimen.	18
Figure 10 – ELS standard specimen.....	18
Figure 11 – CLS standard specimen.	19
Figure 12 – CNF standard specimen.	19
Figure 13 – INF standard specimen.	19
Figure 14 – TCT standard specimen.	20
Figure 15 – DENF standard specimen.	20
Figure 16 – Example of crack propagation gauge application in a DCB specimen.	21
Figure 17 – Illustration of the SHPB experimental set up.....	22
Figure 18 – Qualitative explanation of strain rate dependence of a brittle fracture.	23
Figure 19 – VCCT forces and displacements of the nodes used to calculate the DFT.....	28
Figure 20 – Development of the numerical cohesive zone.	29
Figure 21 – Types of shapes of cohesive laws.	30
Figure 22 – Complete mapping of the CZM from ABAQUS.	32
Figure 23 – TAST specimen dimensions.	38
Figure 24 – 4ENF set up with dimensions to reach the analytical solutions (Martin and Davidson 1999).....	42
Figure 25 – Long 4ENF dimensions.	43
Figure 26 – CLS specimen drawing with stresses and moments of each beam part.	44
Figure 27 – CLS specimen dimensions.....	45
Figure 28 – TAST specimens adhesive drying after the application of the bonded tabs.....	46
Figure 29 – Specimens preparation: Application of white paint in TAST specimens, then the speckle pattern in a CLS specimen.	47
Figure 30 – Example of a calibration image with 14x9 (3mm) calibration target.....	48
Figure 31 – 4ENF specimen set up.	48

Figure 32 – DIC AOI of TAST n°3 in warp direction with the essential data.	49
Figure 33 – DIC AOI of 4ENF test n°1 with the displacement points P0 and P3.	50
Figure 34 – DIC AOI of CLS test n°1 with the displacement point P0.	51
Figure 35 – TAST weft crack separation planes of test 1 (left) and test 2 (right).	56
Figure 36 – Long 4ENF test DIC image 2 at 76% of the duration of the test (crack propagation stopped).	63
Figure 37 – Long 4ENF DIC image at 100% of the duration of the test (end of the test).	64
Figure 38 – DIC images taken during the CLS test experiment with highlighted crack length.	64
Figure 39 – Long 4ENF numerical model: Specimen part with planes and partitions.	84
Figure 40 – Long 4ENF numerical model: Mesh of the complete assembly for cohesive element type model.	86
Figure 41 – Long 4ENF numerical model: Interaction module.	86
Figure 42 – Long 4ENF numerical model: Loads.	87
Figure 43 – TAST numerical model: Loads.	88
Figure 44 – CLS numerical model with VCCT: Interaction module.	88
Figure 45 – CLS numerical model: Loads.	88
Figure 46 – ELS numerical model: Loads.	89
Figure 47 – TAST part drawing from CATIA.	ii
Figure 48 – Long 4ENF part drawing from CATIA.	iii
Figure 49 – CLS part drawing from CATIA.	iv
Figure 50 – ELS part drawing from CATIA.	v
Figure 51 – ELS specimen drawing with stresses and moments of each beam part.	xli

Índice de Tabelas

Table 1 – Mixed mode criteria for delamination growth	12
Table 2 – Summary of the literature in SR effect on DFT in Mode I.....	24
Table 3 – Summary of the literature in SR effect on DFT in Mode II	25
Table 4 – Length of the cohesive zone and equivalent value of the parameter R	34
Table 5 – Possible tests advantages and disadvantages.....	40
Table 6 – Number of static tests performed within the test campaign	41
Table 7 – Projection errors from the DIC analysis.....	52
Table 8 – Cohesive Material Properties normalized used in CZM	69
Table 9 – Overshoot errors of the RVE in percentage	77
Table 10 – Element sizes in the longitudinal direction of the specimen part for each type of model	85
Table 11 – Computational times of the CLS viscosity convergence analysis with K=100000.....	90
Table 12 – TAST warp direction numerical results: Max, Min, and Average of the stresses on the crack line.	92
Table 13 – TAST weft direction numerical results: Max, Min, and Average of the stresses on the crack line.	94

Índice de Gráficos

Graph 1 – Contribution of the kinetic energy of the DFT as a function of the loading rate.....	27
Graph 2 – Normalized DFT in Mode II vs Loading rate of some studies reported in Table 3.....	35
Graph 3 – Frictional effect on the relative error of DFT of a 4ENF test with a length of 100 mm.....	43
Graph 4 – 4ENF test n°1 with local (DIC with Eq. (3.21)) and global (machine) displacement.	50
Graph 5 – CLS test n°1 with local (DIC) and global (machine) displacement.....	51
Graph 6 – TAST warp direction tests with 95% confidence region: Load vs Displacement.	52
Graph 7 – TAST warp direction tests with individual linear slope curves: Shear Stress vs Strain.	53
Graph 8 – TAST warp direction tests with 95% confidence region: Shear Stress vs Strain.	53
Graph 9 – TAST warp direction tests 1, 2 and 3: Shear and Transverse Stain along the crack.	55
Graph 10 – TAST weft direction tests with 95% confidence region: Load vs Displacement.	56
Graph 11 – TAST weft direction tests with 95% confidence region: Shear Stress vs Strain.	57
Graph 12 – TAST weft direction tests 1, 2 and 3: Shear and Transverse Stain along the crack line.	58
Graph 13 – Short 4ENF tests with local (DIC with Eq. (3.21)) and global (machine) displacement.....	59
Graph 14 – Short 4ENF experimental results with 95% confidence area: Load vs Displacement.....	60
Graph 15 – Long 4ENF tests and analytical solution: Load vs Displacement.	61
Graph 16 – Long 4ENF test n°2 crack data: Ohm vs Displacement from Crack Gauge n°1.....	61
Graph 17 – Long 4ENF test n°2 Crack vs Displacement points.....	62
Graph 18 – Long 4ENF tests and analytical solution: Crack Length vs Displacement.....	62
Graph 19 – Long 4ENF tests and analytical solution: Compliance vs Crack Length.	62
Graph 20 – Long 4ENF tests and analytical solution: R–Curve.	63
Graph 21 – CLS test 1 and analytical solution: Load vs Displacement.	65
Graph 22 – CLS test 1 and analytical solution: Crack Length vs Displacement.....	65
Graph 23 – CLS test 1 and analytical solution: Compliance vs Crack Length.	66
Graph 24 – CLS test 1 and analytical solution: R-Curve.	66
Graph 25 – CLS Numerical VCCT: G_{II}/G_T Ratio vs Crack Length.....	67
Graph 26 – Long 4ENF Numerical VCCT: G_{II}/G_T Ratio vs Crack Length	67
Graph 27 – Benzegaggh-Kenane curve of the material studied, obtained from experimental results.....	68
Graph 28 – Trapezoidal and Triangle Laws with the same DFT, in other words, the area below the curve...71	
Graph 29 – Illustration of the new cohesive law for Mode I and II with the cohesive material properties.....72	
Graph 30 – Definition of parameters of the trapeze cohesive law.	73
Graph 31 – Mode I stiffness analysis on the RVE.	76
Graph 32 – Mode II stiffness analysis on the RVE.....	76

Graph 33 – Stress vs Displacement of a cyclic loaded RVE in mix mode I+II for both cohesive laws.....	77
Graph 34 – Consistency checks of the state variables: DFT calculation (left) and Damage (right).....	78
Graph 35 – Validation of both delamination modes using UMAT with Strain Rate formulation in an RVE.	79
Graph 36 – Cohesive element of Long 4ENF specimen: Damage and SR vs Displacement.	80
Graph 37 – Long 4ENF numerical UMAT results: Strain-Rate vs Crack Length.....	80
Graph 38 – Stress vs Displacement of the cohesive law with updating strain rate parameters during loading: increase of strain rate (left); decrease of strain rate (right).....	81
Graph 39 – UMAT viscosity convergence results on the CLS test.	89
Graph 40 – TAST warp direction numerical model with and without damage: Load vs Displacement.	90
Graph 41 – TAST warp direction numerical and experimental results: Load vs Displacement.....	91
Graph 42 – TAST warp direction numerical and experimental results: Shear Stress vs Shear Strain.....	91
Graph 43 – TAST warp direction numerical results: Stress and Strain vs True distance of the crack line.	92
Graph 44 – TAST weft direction numerical and experimental results: Load vs Displacement.....	93
Graph 45 – TAST weft direction numerical and experimental results: Shear Stress vs Shear Strain.	93
Graph 46 – TAST weft direction numerical results: Stress and Strain vs True distance of the crack line.	94
Graph 47 – Short 4ENF numerical, experimental, and analytical results: Load vs Displacement.	95
Graph 48 – Short 4ENF numerical results: FPZ vs Displacement.	95
Graph 49 – Short 4ENF numerical results: R-Curve.	96
Graph 50 – Long 4ENF numerical results: Ratio G_{II}/G_T vs Crack Length.....	96
Graph 51 – Long 4ENF numerical, experimental, and analytical results: Load vs Displacement.	97
Graph 52 – Long 4ENF numerical, experimental, and analytical results: Crack Length vs Displacement.....	97
Graph 53 – Long 4ENF numerical, experimental, and analytical results: Compliance vs Crack Length.	98
Graph 54 – Long 4ENF numerical, experimental, and analytical results: R-Curve.	98
Graph 55 – Long 4ENF numerical results: FPZ vs Displacement.....	99
Graph 56 – CLS numerical results: Ratio G_{II}/G_T vs Crack Length.	99
Graph 57 – CLS numerical, experimental, and analytical results: Load vs Displacement.	100
Graph 58 – CLS numerical, experimental, and analytical results: Crack Length vs Displacement.	100
Graph 59 – CLS numerical, experimental, and analytical results: Compliance vs Crack Length.....	101
Graph 60 – CLS numerical, experimental, and analytical results: R-Curve.....	101
Graph 61 – CLS numerical results: FPZ vs Displacement.	102
Graph 62 – ELS numerical results: Load vs Displacement.	xliv
Graph 63 – ELS numerical results: FPZ vs Displacement.	xliv
Graph 64 – ELS numerical results: Crack Length vs Displacement.	xlv
Graph 65 – ELS numerical results: Compliance vs Crack Length.	xlv
Graph 66 – ELS numerical results: R-Curve.....	xlv
Graph 67 – Definition of parameters of the trapeze cohesive law.....	xlvii
Graph 68 – Short 4ENF with different top rollers set up: Load vs Displacement.....	lv
Graph 69 – Short 4ENF with different top rollers set up: Crack Length vs Displacement.	lv
Graph 70 – Short 4ENF with different top rollers set up: Compliance vs Crack Length.....	lvi
Graph 71 – Short 4ENF with different top rollers set up: R-Curve.....	lvi

Abbreviations

Area of Interest (AOI).....	50	(LEFM)	8
Benzegaggh-Kenane (B-K)	12	Metal Matrix Composites (MMC)	5
Centre Notched Flexure (CNF)	19	multidirectional (MD)	25
Ceramic Matrix Composites (CMC)	5	opening mode (Mode I)	1
Cohesive Zone Length (l_{cz})	34	Over Notched Flexure (ONF)	17
Cohesive Zone Model (CZM)	13	Polymer Matrix Composites (PMC)	2
Compliance Based Beam Method (CBBM)	12	Representative Volume Element (RVE)	82
Corrected Beam Theory (CBM)	12	Resistance-Curve (R-Curve)	2
Cracked-Lap Shear (CLS)	19	shear mode (Mode II)	1
delamination fracture toughness (DFT)	1	Simple Beam Theory (SBT)	12
Digital Image Correlation (DIC)	48	Split Hopkinson Pressure Bar (SHPB)	22
Double Cantilever Beam (DCB)	13	State Dependent Variable (SDV)	91
Double End Notched Flexure (DENF)	21	Strain Rate (SR)	25
End Loaded Split (ELS)	18	tearing (Mode III)	1
End Notched Flexure (ENF)	13	Thick Adherend Shear Test (TAST)	9
energy release rate (ERR)	1	Three-dimensional (3D)	1
Experimental Compliance Method (ECM)	12	Transverse Cut Tension (TCT)	20
Four Point End Notched Flexure (4ENF)	18	unidirectional (UD)	25
Fracture Process Zone (FPZ)	11	User Material (UMAT)	35
Internal Notched Flexure (INF)	20	Vectorized User Material (VUMAT)	35
linear elastic fracture mechanics		Virtual Crack Closure Technique (VCCT)	13

1 Introduction

Composite materials have witnessed a remarkable increase in their use in the area of aeronautics in recent years, revolutionising aircraft design and performance. These advanced materials, which are made up of two or more separate components, provide remarkable strength-to-weight ratios and durability, making them more important in the pursuit of more efficient and sustainable aircraft solutions. Among the many different forms of composites, laminates and woven composites stand out as the main types, each with their own set of advantages and applications.

Three-dimensional (3D) angle-interlock woven composite is a kind of textile composite. Compared with the laminated composites, 3D woven composite is reinforced by fiber tows on the through-thickness direction. With this reinforcement, the stability and the load endurance of this material are improved significantly. They offer excellent delamination resistance and good response to impact loading. Additionally, 3D weavings exhibit near net shape capabilities, allowing for the production of complex preforms close to the shape of the final part. These characteristics allow 3D weavings to be used in applications for which traditional laminates and 2D composites are not suited, whilst at the same time offering additional economic benefits. Due to these superior properties, 3D woven composite is widely used in astronautics, aerospace and many other high-tech fields (Zhao, Zhang et al. 2017). Despite these advantages, 3D weavings have so far failed to achieve widespread application, which is mainly related to the difficulty of analytically or numerically predicting their complex mechanical behaviour (Gerlach, Siviour et al. 2012).

However, as the aircraft industry depends more on composites, it confronts a number of issues, one of the most serious being delamination. Delamination in laminated composites is a form of damage that results in the loss of stiffness and strength due to the separation of adjacent layers. This type of damage can easily escape detection, as it is often embedded within the composite structure and not visible from the surface (Magnus 2019).

Delamination is a critical failure mode when composites are subjected to different loadings, such as low velocity impacts, where this failure mode can introduce considerable structural stiffness reductions without any external signals of damage. The interlaminar delamination fracture toughness (DFT) of a composite material is given by the interlaminar fracture energy release rate (ERR), which is usually characterised by linear elastic fracture mechanic (LEFM) approaches. ERR can be measured for any of the three possible crack propagation modes: opening (Mode I), shear (Mode II) and tearing (Mode III). Mode I has been considered to be the most critical crack propagation mode because it has the lowest associated fracture energy release rate (Blackman, Dear et al. 1995), but Mode II is the main delamination mode that occurs in impact.

Delamination fracture toughness during propagation must be measured for design reasons. A Resistance-Curve (R-Curve) can be used to describe the behaviour. The R-curve

behaviour is an essential crack shielding mechanism during delamination growth, which performs as increased fracture resistance alongside delamination propagation. The contribution of the R-curve part must be included to appropriately estimate delamination propagation (Liu and Chen 2019).

Impact damage (for example, a bird strike) can cause debonding failure of these interfaces, resulting in delamination mainly in Mode II. Understanding delamination initiation and precisely predicting the extent of delamination damage due to impact loading is still a significant challenge in composite structure design. The proper knowledge of the R-Curve and the influence of strain rate effects is critical. The increasingly common use of cohesive zone models for delamination prediction in general, and under impact loading in particular, need accurate DFT values over a wide range of strain rates (Wiegand, Hornig et al. 2014).

Several publications have determined that composite material mode I interlaminar fracture toughness is rate dependant. However, different rate dependency tendencies for identical materials have been documented. The various specimen geometries, loading systems, measurement techniques, data reduction methods, and dynamic considerations used in these investigations have been identified to these variations (Zabala, Aretxabaleta et al. 2015). Although, for Mode II, the strain rate effects in the DFT when considering a 3D woven material is lacking in research. This work will try to fill this gap.

Impact loading's high strain rates can induce considerable changes in mechanical properties. These strain rate effects are classified into two types: (1) the rate-dependent deformation of composites prior to strain softening, and (2) the rate-dependent failure process happening in the fracture process zone after strain softening begins, when microcracks develop, coalescence, and develop into the specimen (Ma, Liu et al. 2021). These effects have been mostly identified in Mode I, where strain rate usually had a greater effect in Mode I than in Mode II (Ribas, Akhavan-Safar et al. 2023).

This phenomenon, has been a focus of study and development since it can endanger structural integrity and raise safety issues in aviation. Understanding and preventing delamination is critical to realising the full potential of composite materials in aeronautics and assuring the progress of aerospace technology.

The development of appropriate experimental methods to measure interlaminar fracture toughness under quasi-static and dynamic loading conditions is essential to the design and analysis of composite structures.(Liu, Nie et al. 2018)

1.1 Objectives of the Project

As part of the LEAP engine project, Safran Aircraft Engines designed and certified special materials called Polymer Matrix Composites (PMC).

Within the framework of the LEAP engine project, Safran Aircraft Engines designed and certified components constructed using PMC. These materials are composed of a combination of organic (polymeric) matrices and reinforcing fibers, typically carbon or glass fibers. These composites exhibit exceptional strength-to-weight ratios and are known for their outstanding mechanical properties, making them ideal for aerospace applications.

Furthermore, Safran Aircraft Engines proposed the incorporation of a 3D woven architecture in these parts. This innovative approach aimed to enhance impact resistance and minimize the risk of delamination damage. However, a comprehensive understanding of the delamination behaviour of these materials especially when subjected to high strain rates, remains poorly understood.

In the context of this thesis, the objectives are as follows:

- To characterize the delamination properties of the 3D woven PMC composites, both under static and dynamic conditions.
- To develop and recommend numerical simulation methods suitable for modelling delamination in these materials.

1.2 Structure of the Thesis

The objectives of this project are therefore multiple. First, it is necessary to constitute the state of the art on fracture mechanics applied to the study of delamination, for both static and dynamic loadings. This work must make it possible to identify the existing models and their field of validity, the quantities/physical parameters to be measured/ characterized as well as the experimental means that can be implemented.

Then, an experimental campaign will make it possible to implement the experimental methods decided in the prior section. The experiments will be used to: evaluate the compatibility between the existing tests and the 3D woven composites; identify the particularities of the methodology and analysis of the Mode II delamination tests; obtain the cohesive properties for interlaminar crack propagation.

Finally, a numerical simulation of the tests will be carried out. A User Material will be developed for implementation of the strain rate effects within the cohesive zone model. The models will use the physical parameters extracted from the tests and the parameters of the cohesive law. These simulations will be compared to the experimental results to verify the predictability of the numerical models.

2 State of art

2.1 Composite Materials

Composite materials are made up of two materials that work together to produce greater properties than the constituents alone. The two main constituents considered here are: A reinforcement, which is responsible for the load carrying and for providing the composite material with its major strength and stiffness, and a matrix that binds the reinforcement, transfers external loads to the reinforcement, protects the reinforcement from the surrounding environment, and provides the shape and surface appearance of the composite system.

The unique balance of properties of composite materials is due to the appropriate combination of matrix and reinforcing fibers. However, structural characteristics such as strength and stiffness are mostly determined by the specific property of the reinforcing phase.

There are three main families of composites, depending on the type of matrix used (Mouritz 2012):

- Polymer Matrix Composites (PMC), which are the most common composites in industry. There are two types: thermoset and thermoplastic. These matrices can also be called “organic” because they are made from carbon.
- Metal Matrix Composites (MMC) used mainly in aerospace-oriented applications, for example copper, aluminium, or steel.
- Ceramic Matrix Composites (CMC), for applications in environments with high temperature, usually made from carbon (C), special silicon carbide (SiC), and alumina (Al₂O₃).

In this thesis, the focus is on a thermoset matrix, namely an Epoxy resin matrix. Because of its superior mechanical qualities, Epoxy is an excellent match for carbon fibres in the formation of composite materials for highly structural applications (Daniel and Ishai 2006).

The reinforcements can be composed of many different materials, such as aramid (Kevlar), carbon or graphite, fiberglass, wood and many other depending on the objective of the composite (Alderliesten 2018). The material in analysis has carbon fibers, which have the highest modulus, but the lowest strain-to-failure. The way in which the carbon fibers are assembled is the particularity of this material. To understand this assembly, one needs to know the denominations of the directions and architectures of composite materials.

A lamina, or ply, is a plane (or curved) layer of unidirectional fibers or woven fabric in a matrix. The lamina is an orthotropic material with principal material axes in the direction of the fibers (longitudinal), normal to the fibers in the plane of the lamina (in-plane transverse),

and normal to the plane of the lamina (Alderliesten 2018). The planes and directions of a lamina are illustrated in Figure 1. The direction of the fibers is denominated as longitudinal (L). Laminates are usually stacked in the thickness direction (Z) which create the interlaminar plane $P2$. In this plane, besides the longitudinal direction, there is the transverse direction (T). The other two planes are considered intralaminar planes (Alan Baker 2004).

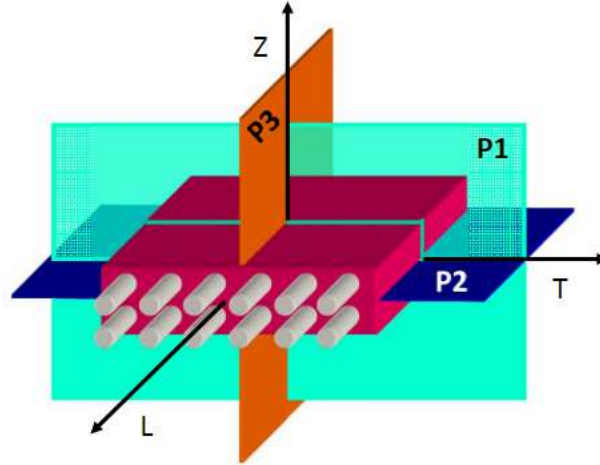


Figure 1 – Composite laminate directions and planes.

The material in analysis is a woven composite, where the longitudinal direction is called the warp direction, while transverse is named as weft direction, since there are fibers in this direction in a woven composite. When there are fibers in the thickness direction, the material can be denominated as a 3D woven (Ansar, Xinwei and Chouwei 2011). These types of architectures of fibers are further explained in the next section.

2.1.1 Woven architectures

Woven fabrics can be of 2D or 3D formats, produced from interlocking bundles of long fibres, for applications requiring good formability, good impregnation, and high damage resistance.

- 2D fabrics have less undulation, exhibiting higher mould conformability (property known as drapability).
- 3D fabrics are distinguished by their interlaminar strength, due to the fibres in the thickness direction.

There are three main 2D fabric architectures, plane weave, satin weave, and twill weave, as Figure 2 illustrates.

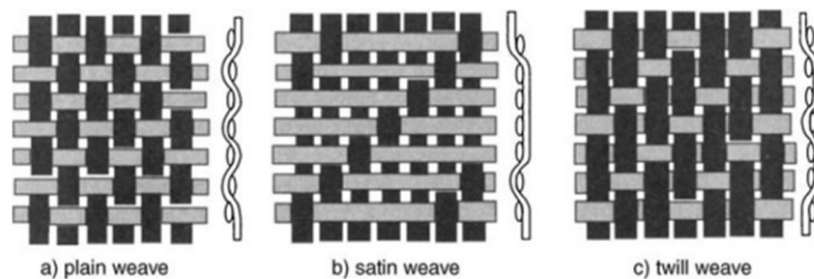


Figure 2 – 2D woven fabric architectures.

When there are fibres in the thickness direction, either in the weft direction or in the warp direction, a fabric is called “3D interlock warp” or more rarely “3D interlock weft”.

There are four categories of 3D warp interlock fabric. Two geometric parameters are used to distinguish 3D warp interlock fabrics. The first parameter corresponds to the angle taken by the yarns of the binding warps in the thickness: either angled (A) or orthogonal (O). The second parameter corresponds to the bonding depth of these warp threads in the thickness: either in layer to layer (L) or through the thickness (T). By combining these two parameters with their two respective values, we then obtain four groups of 3D warp interlock fabrics (Ansar, Xinwei and Chouwei 2011, François BOUSSU and DECRETTE 2021).

Depending on the combinations and positions of the warp yarns in the multilayer woven structure, a wide variety of 3D structures can be obtained. Unlike 2D fabrics whose variation in bonding depends on the woven weave, 3D warp interlock fabrics reveal more modular options allowing for a greater number of woven patterns.

3D warp interlock fabrics have technical and economic advantages over other reinforcements and replace laminates in applications where the latter are no longer suitable. However, this type of fabric also has some drawbacks inherent in its manufacture and its specific architecture.

As previously stated, Safran Aircraft Engines now uses 3D woven composites for certain parts of these engines, where the material in analysis is a 3D woven angle warp interlock.

The main advantages of 3D woven are (François BOUSSU and DECRETTE 2021):

- Resistance to delamination ensured by the reinforcement in the thickness, by the binding warp yarns for fabrics 3D warp interlocks.
 - Enhanced damage tolerance and impact resistance
 - Tailored reinforcement: Manufacturers can tailor the orientation and distribution of fibres in 3D woven composites to meet specific load requirements.
 - Strong material cohesion due to the binding threads that connect the layers.
 - Reduced material waste: When compared to traditional manufacturing methods, 3D weaving processes can be more efficient, resulting in minimum material waste.
- While the disadvantages are:
- Anisotropic properties: While fibre orientation can be controlled, anisotropic qualities exist in 3D woven composites which are difficult to numerically simulate.
 - Production of 3D warp interlock fabrics on a large scale is limited, not allowing to reduce the cost of manufacture, since designing and producing tooling for 3D woven composites can be more expensive and challenging due to the complex geometry of some parts.
 - The complex architecture may create unpredictable manufacturing errors that lead to a lower overall strength of the material, and less reliability of the material. These errors can be, for example, voids between the undulations of the fibers and binding threads, the friction between warp and weft fibers, and uneven dispersion of the matrix.

These difficulties in manufacture are one of the main difficulties in all types of composites, and 3D woven enhance the probability of occurring issues. These issues lead to failure in various types. In the next section the failure modes are introduced with the main focus in this work being delamination, which composites are prone to. Although 3D woven architectures reduce delamination probability by having a higher delamination resistance, it is still required a study on how these types of materials behave with interlaminar delamination.

2.1.2 Failure Modes of Composites

Fiber kinking, fiber breaking, matrix cracking, fiber/matrix interface debonding, delamination, or a combination of these causes can all lead to composite failure. When fiber buckling occurs, the matrix around the fibers supports them, but the laminate's compressive stiffness and strength are reduced. The load is transmitted around the failing fiber by the surrounding matrix, which functions as a bridge around the break, and this phenomenon is known as fiber bridging. Matrix cracking promotes moisture absorption into the composite, lowering the laminate's matrix-dominated stiffness (load carrying capability orthogonal to the fiber orientation), and may advance into the interface between neighbouring plies, resulting in delamination (Magnus 2019). The topic of this thesis is delamination, a typical failure mode in laminated composites. Delamination is the separation of neighbouring layers, which can occur during manufacture or afterwards when stresses are applied to the composite. Delamination lowers the composite's bending stiffness, strength, and load bearing capacity in compression. The delamination may expand to a critical size under stress, at which point its growth becomes unstable and its strength rapidly degrades.

The study of delamination and prediction of crack initiation is done with fracture mechanics, which will be explained in the next section.

2.2 Static Interlaminar Fracture Testing

The failure of composite materials can be caused by the existence of imperfections, singularities or zones with a high stress gradient which lead to the start of cracks and eventually the entire failure of the structure. The evolution of these imperfections, which are represented by a crack, constrain the assembly's resistance, and are usually analysed using linear elastic fracture mechanics (LEFM). Three fundamental ways of crack propagation are illustrated in Figure 3.

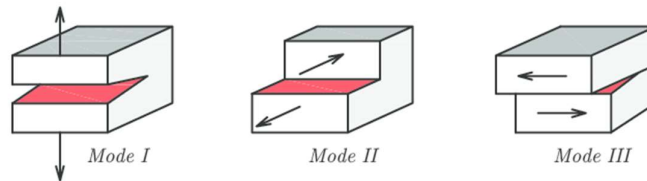


Figure 3 – Delamination modes.

Fracture mechanics is separated into two major forms of analysis, both of which originated from the work of AA Griffith (Griffith 1921) and GR Irwin (Irwin 1957). The first is a method known as the local stress approach, in which fracture propagation is controlled by a stress intensity factor K . When this component surpasses a critical threshold, K_c , the crack advances. The second is an energetic, global method in which the crack's progression is determined by a rate of energy restitution G . When the rate of energy restitution reaches the critical rate, G_c , which corresponds to the total of the surface energies and the energies dissipated during cracking, the crack propagates.

The energy approach outperforms the local stress approach. The rate of energy restitution is reasonably straightforward to estimate using experimental or analytical methods, allowing researchers to avoid examining the extremely complicated stress field near the crack tip. Furthermore, analytical formulations for the stress intensity factor in anisotropic materials are uncommon. As a result, only the energy strategy will be covered in depth.

The basic premise underlying delamination is that it occurs when the separation stress between plies exceeds the bonding strength. The propagation of delamination involves energy dissipation using fracture mechanics theory (Tabiei and Zhang 2018).

Many failure criteria for delamination initiation and propagation have been proposed. In the next subsections, it will be shown some of these criteria, how to obtain the experimental values, and other considerations.

2.2.1 Delamination Initiation Criteria

The initiation of delamination is analysed from the stress level. The simplest criterion for delamination to start is when the interlaminar stress is higher than the interlaminar bonding strength, as described in Eq. (2.1) for Mode I.

$$\sigma_{zz} \geq T_{zz} \quad (2.1)$$

For coordinate designation, x and y indicate the laminar plane, and z specifies the thickness direction; consequently, σ_{zz} is the through thickness stress. The tensile strength between layers is denoted by T . Although simple to apply, this criterion is inaccurate when a 3D stress state occurs since shear stress cannot be ignored.

Ye Lin (Lin 1988) suggested a quadratic stress criteria to account shear stress, but separated the tension and compression scenarios and used average stress along the free edge. According to Ye Lin's criterion, delamination initiates when the Eq. (2.2) is met:

$$\begin{cases} \left(\frac{\overline{\sigma_{zz}}}{T}\right)^2 + \left(\frac{\overline{\tau_{xz}}}{S}\right)^2 + \left(\frac{\overline{\tau_{yz}}}{S_T}\right)^2 \geq 1 & \text{if } \overline{\sigma_{zz}} > 0 \\ \left(\frac{\overline{\tau_{xz}}}{S}\right)^2 + \left(\frac{\overline{\tau_{yz}}}{S_T}\right)^2 \geq 1 & \text{if } \overline{\sigma_{zz}} \leq 0 \end{cases} \quad (2.2)$$

where $\overline{\sigma_{zz}}$, $\overline{\tau_{xz}}$, and $\overline{\tau_{yz}}$ are the average stresses over a distance from the free edge in through-the-thickness and transverse directions. The transverse tensile and in-plane shear strengths are denoted by T and S , respectively, while the through thickness shear strength is denoted by S_T . Because the strength in the through thickness direction is often difficult to acquire, several studies approximated its by replacing it with the shear strength in the thickness direction ($S_T = S$). This criterion is widely used in numerical models such as the Cohesive Zone Models (CZM), which will be discussed in Section 2.4.1.2.

Within ABAQUS, there are four crack initiation criteria: maximum stress, quadratic stress, maximum strain, and quadratic strain criterion. Due to the high sensitivity of failure initiation to the strain and displacement, a stress-based criterion gives an accurate failure prediction as compared to other models (Moslemi and Khoshnavan 2015).

Other criteria do exist, such as the modified Tsai-Wu failure criterion or Christensen's formulation, but for some specific cases they have their issues, especially when involving compressive or very anisotropic behaviour such as it occurs in woven composites. So, the simpler formulation of Ye Lin is the most effective for most cases.

In order to determine experimentally the crack initiation, Althof (Althof and Neumann 1974) proposed the Thick Adherend Shear Test (TAST), Figure 4. The use of a short overlap in these specimens allows rotation of the specimen to be completely minimised, resulting in a stress state entirely dominated by uniform shear. The goal of this test is to recover the maximum stress at the level of the sheared zone before there is damage in the specimen.

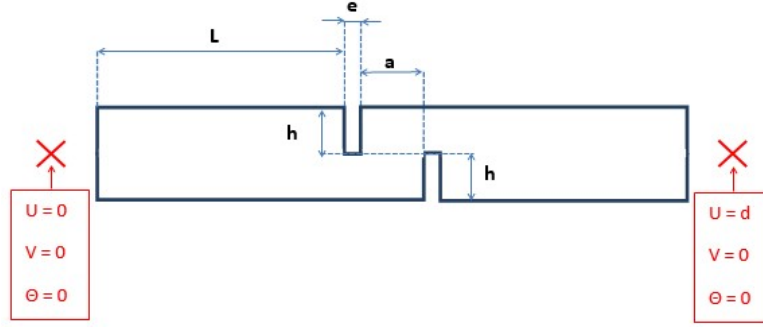


Figure 4 – Thick Adherend Shear Test (TAST) to simulate crack initiation.

The impact of interlaminar shear strength on the Load vs Displacement and R-Curve (delamination fracture toughness vs crack length) was found to be minimal on tests that focus on the R-Curve. This is a significant finding since interlaminar opening strength (Mode I) is an essential model parameter that is difficult to get empirically, and so is often assumed (Silva, de Moura and Morais 2006).

The shear stress along the fracture plane is not uniform as a result of the specimen design, as stress concentrations at the notches are inevitable. However, for a comparable design, it has been demonstrated that the observed strength values correlate well with the uniform shear stress level away from the notch grounds (Gerlach, Siviour et al. 2012). The experimental and numerical analysis will try to confirm these conclusions.

For a woven composite, the TAST can address both interlaminar shear strengths (warp and weft), since with the very anisotropic material can produce different interlaminar shear strengths according to the direction of the test. Furthermore, the TAST has been used in strain rate dependency studies successfully (Gerlach, Siviour et al. 2012). Gerlach et al. found an increase in the average strength with the increase in loading rate, for both warp and weft direction.

The TAST can determine the shear modulus and interlaminar shear strength from the shear stress-strain curve. Elastomeric materials, in general, display nonlinear stress strain behaviour, therefore defining the modulus is difficult. At low shear stresses, however, they satisfy Hooke's law and the modulus may be calculated (Banea and Silva 2009).

2.2.2 Delamination Fracture Toughness (DFT)

To characterise the propagation or non-propagation of a crack, an energy, and more specifically, the rate of restitution of energy or Energy Release Rate (ERR), G , is used. The ERR was proposed by AA Griffith (Griffith 1921) in the 1920s and significantly reformed and explained by GR Irwin in the 1950s (Irwin 1957). It consists of carrying out the energy balance during crack propagation, Eq. (2.3):

$$\Delta W_{ext} = \Delta E_{el} + \Delta E_c + \Delta E_d - G \cdot \Delta S \quad (2.3)$$

The interaction of external factors between two states ΔW_{ext} is divided into four terms. The first is the variance in elastic energy, ΔE_{el} , which is the stored energy in the structure in the form of compressed springs that will be released as soon as the external stress goes away. The second is the change in kinetic energy, ΔE_c . This term is zero in a static problem. The variation of dissipated energy, ΔE_d , is the third term and indicates the energy wasted in the structure, such as plasticity. This energy is irreversibly gone and so cannot be recovered. Finally, the energy released (or restored if crack is closing) by the advancing crack, $G \cdot \Delta S$, is the energy that the crack will release by advancing from a surface S .

Thus, the energy released by the crack to travel forward one area unit, may be defined as follows:

$$G = \frac{\Delta W_{ext} - \Delta E_{el} - \Delta E_c - \Delta E_d}{\Delta S} \quad (2.4)$$

For a static case, the most common in the literature, the kinetic energy is null (or negligible). LEFM is also employed, meaning that the structure is assumed elastic, where the dissipated energy around the crack tip is negligible. This results in Eq. (2.5) that defines the ERR.

$$G = \frac{\Delta W_{ext} - \Delta E_{el}}{\Delta S} = \frac{\partial(F - U)}{B \partial a} \quad (2.5)$$

This energy release rate can be calculated even if the crack does not propagate. The energy the crack needs to release to propagate is the critical ERR, G_c . It can also be called the Delamination Fracture Toughness (DFT). This notion DFT characterizes the ability of a material to resist crack propagation; the lower it is and the more fragile the material, whilst the greater it is and the more the material is tenacious. When dimensioning a structure, it is required to ensure that a crack in the structure will not propagate. Therefore, the relation $G < G_c$ must be met.

In practise, however, the situation is more complicated since DFT is not a constant and tends to increase with crack length, a . When a fracture propagates, there is a zone of damaged material surrounding the crack's tip. This zone is known as the Fracture Process Zone (FPZ), as seen in Figure 5. And there is energy expended in the development of this FPZ, hence the different ERR when the crack increases.

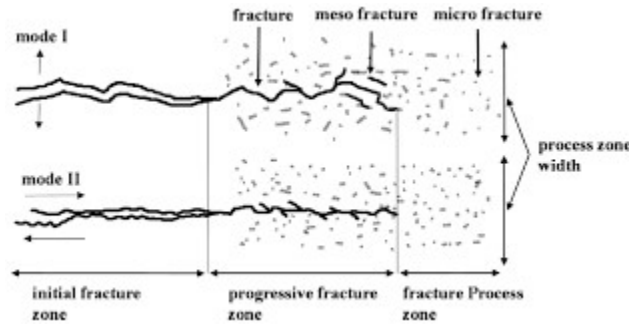


Figure 5 – Fracture Process Zone illustrated for delamination in Mode I and Mode II.

The increase in DFT with crack length caused by the expansion of the FPZ is referred to as the R-Curve (for resistance curve). In reality, the size of the FPZ tends to expand at the start of propagation and then stabilise after a while, which explains why the R-Curve frequently tends to an asymptote.

The stability of a test can also be observed through a Load vs Displacement graph in which there are three phases. The elastic zone is where the material deforms elastically. This zone is a straight line passing through the origin and having a slope equivalent to the compliance with the value of the pre-crack, a_0 . The second zone is the propagation zone, which is where the crack propagates through the material. The final zone is the zone after the crack is fully propagated. The propagation is stable if the relation in Eq. (2.6) is met.

$$\frac{\partial G(a)}{\partial a} < \frac{\partial G_c(a)}{\partial a} \quad (2.6)$$

It is common to assume the DFT constant during propagation, so, the relation changes to Eq. (2.7).

$$\frac{\partial G(a)}{\partial a} < 0 \quad (2.7)$$

Unstable initiation prevents propagation toughness measurements. Only one data point is obtained, so the R-curve is not possible to be attained if the propagation is unstable (De Moura 2008, de Moura and de Morais 2008).

It is possible to define ERR for the three delamination modes. The total ERR is calculated through the sum of the ERR of each mode, as Eq. (2.8) expresses.

$$G = G_I + G_{II} + G_{III} \quad (2.8)$$

The relation between these delamination modes has been investigated a significant amount. A common consideration is joining both shear modes. The mixed mode delamination criteria often use the mixed mode ratio, $G_{II}/(G_{II} + G_I)$, as a variable. The denominator is the total ERR, G_T . Table 1 summarizes the most common mixed mode delamination propagation criteria used in the industry. Delamination occurs when the conditions in these equations are met (Tabiei and Zhang 2018).

One benefit of Benzegagh-Kenane (B-K) law over the Power law is that it only requires one parameter, η , to calibrate from experiments, whereas the Power law requires two, α and β . It has also been reported that the B-K law captures the mixed-mode ratio change effectively (Tabiei and Zhang 2018). All these factors have made B-K law the most widely used mixed mode criterion for delamination propagation, both in VCCT and CZM.

Table 1 – Mixed mode criteria for delamination growth

Criterion name	Criterion expression
Power Law	$\left(\frac{G_I}{G_{Ic}}\right)^\alpha + \left(\frac{G_{II}}{G_{IIc}}\right)^\beta \geq 1$
Exponential haeckel law	$G_I + G_{II} \geq G_{IIc} + (G_{Ic} - G_{IIc})e^{\gamma(1-N)}$
B-K law (Benzeggagh and Kenane 1996)	$G_T \geq G_{Ic} + (G_{IIc} - G_{Ic})\left(\frac{G_{II}}{G_T}\right)^\eta$

The DFT of each mode is then required to be calculated. There are many analytical methods. Some examples are listed below:

- Simple Beam Theory (SBT)
- Corrected Beam Theory (CBT)
- Compliance Based Beam Method (CBBM).

From experimental results is also possible to attain the DFT, using these methods:

- Area Method
- Experimental Compliance Method (ECM).

To predict numerically the experimental results, there are two common ways of simulating the delamination:

- Virtual Crack Closure Technique (VCCT)
- Cohesive Zone Model (CZM).

In the next sections these methods will be analysed, examining the most common test specimens for Mode I and II, the Double Cantilever Beam (DCB) and End Notched Flexure (ENF) tests, respectively.

2.2.3 Analytical Methods for the Mode II DFT

2.2.3.1 Simple Beam Theory (SBT)

To be able to apply this method, three assumptions must be made. The first is that the crack front keeps its shape as the delamination propagates and there is no change in the delamination plane. Next, the crack is assumed to cross the width, B , of the specimen. Finally, the material behaves in a linear elastic way.

The analytical DFT is attained using the initial force, P , and the derivative of the compliance, C , according to the crack length, a , using Eq.(2.9)

$$G_c = \frac{P^2}{2B} \cdot \frac{\partial C}{\partial a} \quad (2.9)$$

Using Castigliano's theorem, the compliance can be calculated with:

$$C = \frac{\delta}{P} = \frac{1}{P} \frac{\partial E_{el}^{total}}{\partial P} \quad (2.10)$$

Where the term E_{el}^{total} is the total elastic energy of the specimen.

The elastic energy can be calculated knowing the stress applied in the beam with Eq. (2.11)

$$E_{el}^{total} = \iint \frac{\sigma^2}{2E} dL_x dA \quad (2.11)$$

where L_x is the length of the beam section, A is the area of cross section, and E is the Young's modulus of the material. The stress is calculated through a structure analysis of the stresses and moments applied in the specimen.

The most common specimen for Mode II delamination is the ENF, Figure 6, where a loading roller moves to apply bending in the specimen. Two rollers are situated below the specimen as the boundary condition.

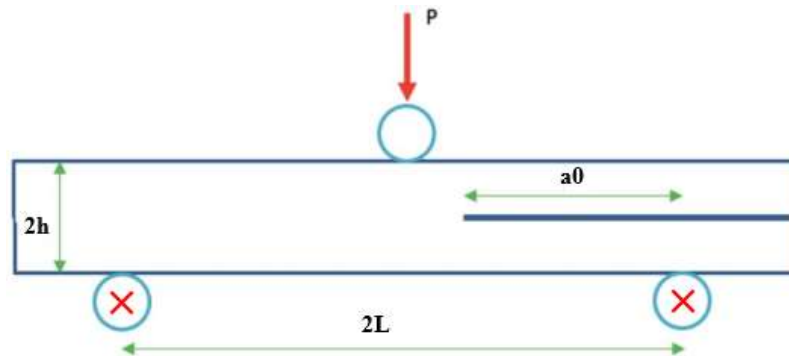


Figure 6 – ENF standard specimen.

The SBT solution for this specimen is:

$$G_{II}^{ENF} = \frac{9P^2 a^2}{16EB^2 h^3} \quad (2.12)$$

The introduction of the load is rather simple, the propagation of delamination is unstable except for very large crack lengths ($a/L > 0.7$) (Davies, Kausch et al. 1992) The majority of studies on the ENF test use an a/L ratio of 0.5, thus the propagation is therefore unstable.

2.2.3.2 Corrected Beam Theory (CBT) and Compliance Based Beam Method (CBBM)

There are many other beam theories and methods, but in this subsection two different ones will be shown. One is just an evolution of the SBT, while the second is a more complex method, with great advantages later explained. The analytical solutions will only be shown for the ENF specimen, since it's the delamination mode in analysis in this thesis.

The CBT is based on the previously presented beam theory, adding an extra term to it to consider the influence of different parameters. For example, Carlsson et al. (Carlsson, Gillespie Jr and Pipes 1986) showed that the interlaminar shear strain could influence the evaluation of the fracture toughness in mode II. This influence can however be minimized by using beams with a low thickness/length ratio. The analytical solution using CBT is:

$$G_{II}^{ENF} = \frac{9P^2 a^2}{16EB^2 h^3} \left(1 + 0.2 \frac{E}{G_{13}} \left(\frac{h}{a} \right)^2 \right) \quad (2.13)$$

where G_{13} is the shear modulus. This method still needs the measure of the crack length.

The CBBM method (de Moura and de Morais 2008) was formulated to eliminate the need of measuring crack growth during testing. To overcome these constraints, a calculation starting from a concept of equivalent crack is proposed. The latter depends only on the compliance of the sample during the ENF test, which using beam theory can be written as:

$$C = \frac{3a^3 + 2L^3}{8EBh^3} + \frac{3L}{10G_{13}Bh} \quad (2.14)$$

where C is the compliance, a is the crack length, L is the half length of the tested sample, E is the Young's modulus, B is the width, h is the half height and G_{13} is the shear modulus.

Since the flexural modulus of the specimen, E_f , plays a fundamental role in the Load vs Displacement plot, the latter can be expressed using the initial compliance C_0 and the initial crack length a_0 , using Eq. (2.15).

$$E_f = \frac{3a_0^3 + 2L^3}{8Bh^3 C_{0\ corr}} \quad (2.15)$$

where the corrected initial compliance is:

$$C_{0\ corr} = C_0 - \frac{3L}{10G_{13}Bh} \quad (2.16)$$

This procedure takes into consideration the variability of material properties between different specimens as well as several effects not included in beam theory, such as stress concentrations near the crack tip, contact between arms of the specimen in the region of the pre-crack, and the effects of crack tip displacement and rotation. In reality, even in the elastic domain, these phenomena impact the behaviour of the specimen and, as a result, the Load vs Displacement curve. The computed bending modulus is used to account for their effect in this process. By considering compliance and the idea of equivalent crack during propagation, the influence of FPZ may be considered. As a result, to account for the impact of the FPZ during crack propagation, Eq. (2.17) includes a correction of the true length.

$$a_e = a_0 + \Delta a_{FPZ} = \left[\frac{C_{corr}}{C_{0\ corr}} a_0^3 + \frac{2}{3} \left(\frac{C_{corr}}{C_{0\ corr}} - 1 \right) L^3 \right]^{\frac{1}{3}} \quad (2.17)$$

Then, the DFT for the ENF specimen using CBBM is calculated with:

$$G_{II}^{ENF} = \frac{9P^2 a_e^2}{16E_f B^2 h^3} \quad (2.18)$$

Using this methodology, the critical energy release rate can be obtained just from the Load vs Displacement curve. The results showed that classical beam theory-based techniques might underestimate the DFT. In fact, even if reliable crack position observations were obtained, the later approaches fail to account for the FPZ. CBBM, on the other hand, has been proven to be quite accurate. (De Moura 2008, de Moura and de Morais 2008)

2.2.4 DFT Experimental Calculation

2.2.4.1 Area Method

Among the simplest methods to implement, the method of areas uses the data of the Load vs Displacement curve, to determine the energy dissipated during crack propagation. This method is applied to materials with a quasi-brittle fracture, which makes it possible to easily identify the phases of propagation of the crack, in particular a discrete increase in the crack length, Δa . The method then uses Eq. (2.19) to attain the DFT.

$$G_c = \frac{1}{2B\Delta a} (P_i d_{i+1} - P_{i+1} d_i) \quad (2.19)$$

where B is the thickness of the specimen, the force and displacement are taken from the points shown in Figure 7, and Δa is the difference in crack length between the point i and $i+1$.

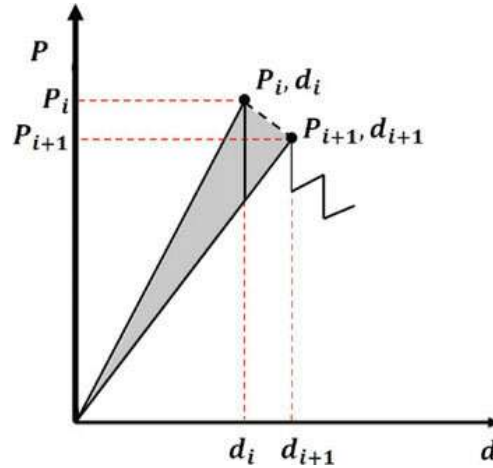


Figure 7 – Illustration of the area method.

In practice, this approach is appealing due to its ease of implementation, but it is not particularly exact, even when the crack propagation is substantial. It is likewise extremely unusual and frequently discouraged by the standard.

2.2.4.2 ECM

This method originates from a simpler version, the Compliance Method (CM), which uses the LEFM considerations and compliance equations. For composite materials, this means that nonlinear phenomena (such as plasticity and damage) must be very localized so as not to alter the linear elastic response of the material too much. This method therefore is applied to quasi-isotropic and orthotropic laminates but is no longer valid for laminates or woven composites with strongly oriented plies whose behaviour is highly elastic-ductile. For Mode II delamination, since the compliance according to the crack length of the ENF specimen is a cubic curve, its DFT using the CM is calculated with Eq. (2.20).

$$G_{II}^{ENF} = \frac{3mP_{max}^2a_0^2}{2B} \quad (2.20)$$

where m is experimentally calculated with a fitting curve.

To consider the non-linear effects, another compliance method was established, the Experimental Compliance Method. It also relies on the Load vs Displacement curve of specimens, but also uses the Compliance vs Crack Length plot fit curves to arrive at derivative of this plot at each crack length, $\frac{\partial C(a)}{\partial a}$. It is required the record the crack length during the experimental test. Then a polynomial regression is used to calculate the Compliance vs Crack length with the following form:

$$C(a) = \alpha a^3 + \beta a^2 + \gamma a + \lambda \quad (2.21)$$

where C is the compliance, a is the crack length, and α, β, γ , and λ are regression parameters, optimized to fit the plot. For example, β and γ for the ENF specimen should be null or very small. Then a partial derivative is used to get the DFT, as Eq. (2.22) shows.

$$G_{IIc} = \frac{P_{max}^2}{2B} (3\alpha a^2 + 2\beta a + \gamma) \quad (2.22)$$

This method is very effective and makes it possible to measure the DFT throughout the entire crack propagation. This is the most widely used method for the experimental results.

Depending on the type of test, the degree of the polynomial resulting from the fitted curves of the compliance as a function of the crack varies. Eqs. (2.23) are examples of the form of the polynomial obtained depending on the type of test (Fan, Jar and Cheng 2013).

$$\begin{aligned} C^{ENF} &= \frac{3a^3 + 2L^3}{8EBh^3} \\ C^{ELS} &= \frac{3a^3 + L^3}{2EBh^3} \\ C^{4ENF} &= \frac{L^3}{32EBh^3} \cdot \left(1 + \frac{9a}{L}\right) \end{aligned} \quad (2.23)$$

2.2.5 Delamination Mode II Experimental Tests

The ECM, among the analytical and experimental methods, is accepted in the ASTM as the most accurate for mode II delamination. So, it will be the method to be employed. For the DFT analytical equations, the SBT will be utilized to attain these calculated values in the numerical models, since it's the simpler method.

Whilst the mode I delamination test method for composites based on the DCB test has progressed to an international standard, there has been little progress towards the goal of a more complete mode II delamination standard (Blackman, Brunner and Williams 2006). The ENF test is accepted as the standard, but it exhibits unstable crack propagation.

Besides the ENF test, there are many others tests to determine the fracture toughness in Mode II. Most of them use bending to induce a shear load in the specimen. The main objective when establishing the tests is to give reproducible results with an easy-to-perform test. The following subsections describe the existing tests for Mode II delamination.

2.2.5.1 Over Notched Flexure (ONF)

Proposed by Tanaka et al. (Tanaka, Yuasa and Katsura 1998), the ONF specimens and assembly are quite similar to those of the ENF. The sole distinction between the two tests is the position of the loading roller. It is applied to the middle of the specimen for ENF and above the pre-crack for ONF, as Figure 8 displays. This improvement allows for more stable crack propagation. It should be noted, however, that the friction formed between the surfaces impacts the value of the rate of energy restitution. A 60% greater value was seen when compared to the ENF test.

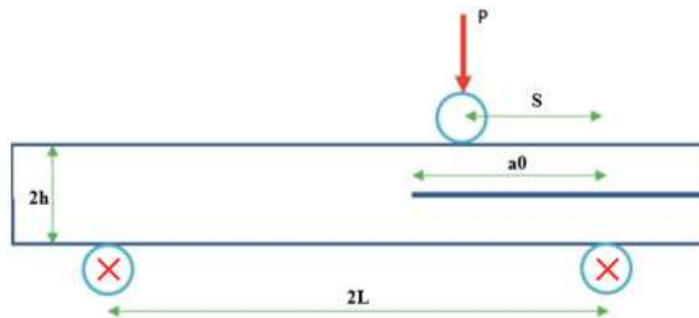


Figure 8 – ONF standard specimen.

2.2.5.2 Four Point End Notched Flexure (4ENF)

Martin and Davidson (Martin and Davidson 1999) presented the four point end notch flexure (4ENF) test, Figure 9, which appeared to overcome many of the mode II testing difficulties found in the ENF test:

- Complex tools/equipment are not required to perform the test procedure.
- A stable crack propagation is obtained when the delamination occurs between the loading rollers.
- A constant crack propagation speed.

However, there are several limitations to this test:

- Additional equipment must be set up for motion, which may impact the results.
- The friction between the two loading rollers may no longer be negligible and can lead to a DFT higher than ENF results (Fan, Jar and Cheng 2013, Parrinello 2018, Liu and Chen 2019).
- Measured DFT can be specimen geometry dependent, with an apparent decreased in DFT with increase in the span length, $2L$, (de Moura and de Morais 2008)

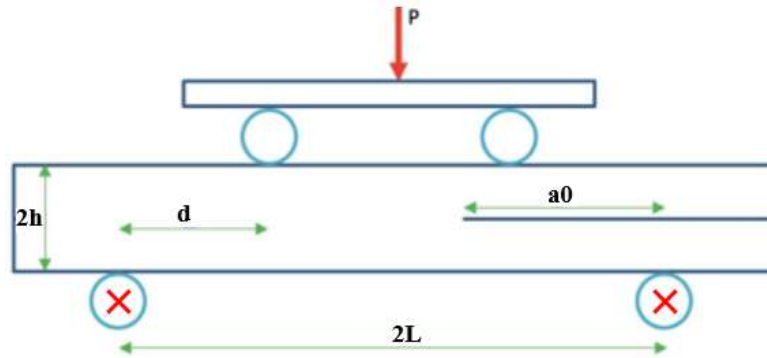


Figure 9 – 4ENF standard specimen.

Furthermore, de Moura and de Morais and Kageyama et al. (Kageyama, Kimpara et al. 1999, de Moura and de Morais 2008) suggest that the loading point height should be minimised. Nonetheless, when the compliance and crack length were accurately determined, the 4ENF specimen seemed adequate when compared to the other Mode II tests (e.g., the ENF and the ELS) (Brunner, Blackman and Davies 2008).

2.2.5.3 End Loaded Split (ELS)

The ELS test, Figure 10, is a standardized test usually preferred for the stability of delamination propagation. A loading block or roller introduces the bending motion, while grips hold the specimen in the vertical direction, leaving the horizontal direction free. The ELS test makes it possible to obtain stable crack propagation if the condition $a_0/L > 0.55$ is respected (Blackman, Dear et al. 1996). Nevertheless, it requires a rather complicated assembly to maintain the conditions of the slippery embedding, thus the DFT result is affected by the clamp variability, and the specimen is prone to large displacements (de Moura and de Morais 2008).

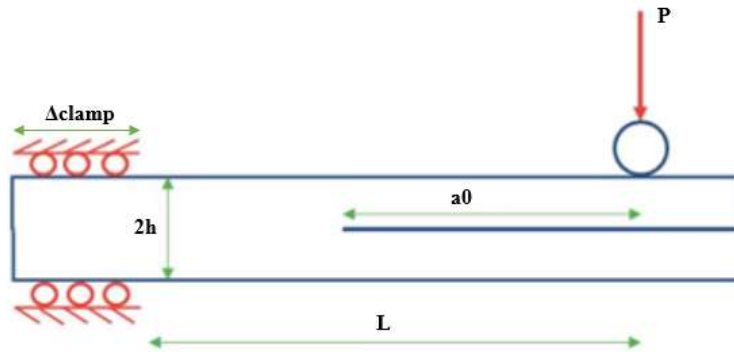


Figure 10 – ELS standard specimen.

2.2.5.4 Cracked-Lap Shear (CLS)

The CLS test is an asymmetrical specimen tensile test. This test was originally designed to characterise specimens in mixed mode I + II. However, if longitudinal guiding is provided by the addition of geometric restrictions on each side of the sample, the specimen is prevented from opening and causing delamination in mode I. Figure 11 shows the standard CLS specimen without the longitudinal restrictions. The force is applied in the centre thickness of the specimen on the longer arm. This test has been proven to have stable crack propagation (Guimard, Allix et al. 2009).

The use of a CLS configuration is supported by the difficulties of converting the classical test, the ENF specimen, into dynamics due to the complexity of the required assembly and the existence of large frequency couplings due to the bending vibration modes.

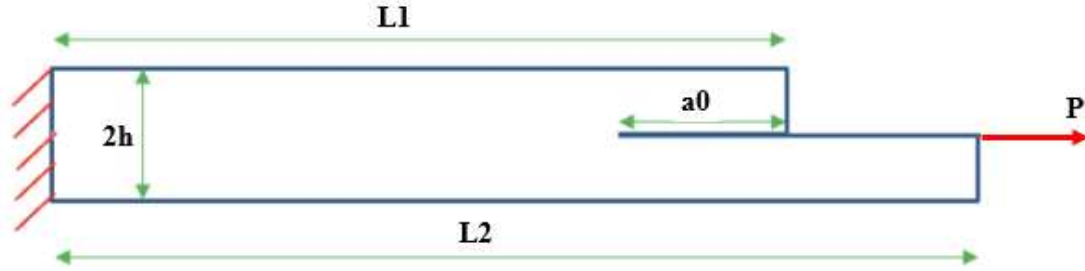


Figure 11 – CLS standard specimen.

2.2.5.5 Centre Notched Flexure (CNF)

The CNF test, like the ENF, is a 3-point bending test. However, the location of the crack differs. In reality, the specimens do not have artificial cracks emerging on one end, but rather a centre crack formed during the manufacturing process, Figure 12. This test procedure, among other things, prevents the formation of intralaminar fractures.

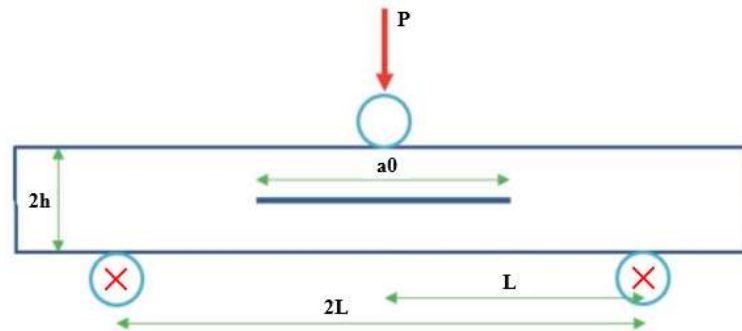


Figure 12 – CNF standard specimen.

2.2.5.6 Internal Notched Flexure (INF)

This type of test is similar to the one presented above, the CNF. The main difference between the two tests is the placement of the specimen in the 3-point bending device. The INF test applies the load asymmetric with respect to the initial crack, with one tip of the crack being much closer to the load than the other, Figure 13. This test has the advantage of promoting stable crack propagation. A slightly higher value of G_{IIC} compared to the ENF tests was obtained, which according to the authors is possible due to the fibre bridging that occurred on the INF specimen (Fan, Jar and Cheng 2013).

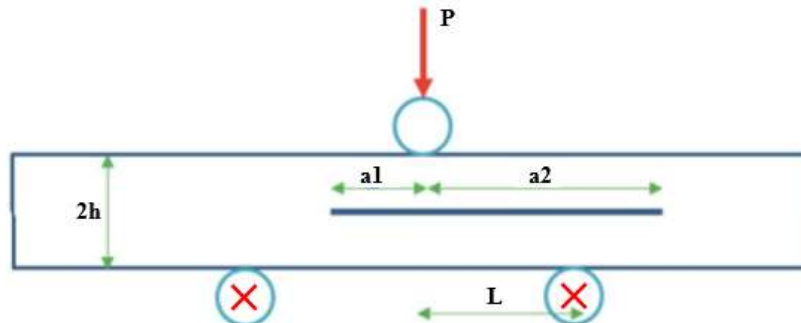


Figure 13 – INF standard specimen.

2.2.5.7 Transverse Cut Tension (TCT)

The TCT test is a tensile test in which the sample has two fabricated cracks produced during the manufacturing process. Furthermore, a crack perpendicular to the direction of the fibres connects these two cracks in the centre of the specimen. Shearing is caused by the differential in stresses between the inner and outer layers, and four fractures begin at the level of the cut. According to Hahn et al. (Hahn, Channammagari et al. 2022), this test results in unstable crack propagation, and the standard TCT is illustrated in Figure 14

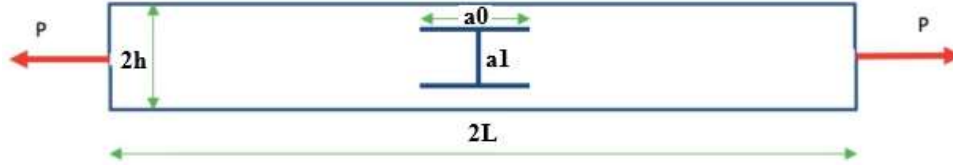


Figure 14 – TCT standard specimen.

2.2.5.8 Double End Notched Flexure (DENF)

The DENF test is a 3-point bending test with both ends having a pre-crack, as Figure 15 illustrates. In the literature, this test has had relatively little use. Moreover, the authors using it (Cantwell 1997, Berger and Cantwell 2001, Berger and Cantwell 2001) do not cite any information as to the advantages and the drawbacks of this method. The crack propagation is unstable, and from the specimens tested by the authors, with increasing in temperature, the crack propagation starts to be stable.

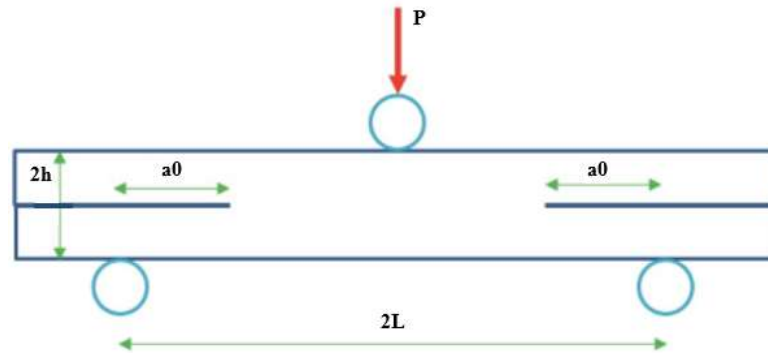


Figure 15 – DENF standard specimen.

2.3 Dynamic Considerations

Impact delamination is classified into two types: low-velocity impact and high-velocity impact. Low velocity impact can be classified as quasi-static occurrences with upper limits ranging from one to tens of metres per second. Low velocity impacts are frequently caused by tool drops, runway debris, unintentional stepping, hail storms, and other factors (Richardson and Wisheart 1996). These impacts will be denominated as dynamic loadings from this point forward.

When dynamic loading is considered, the kinetic energy is no longer negligible in the calculation of the ERR. For example, Smiley and Pipes (Smiley and Pipes 1987) started from the definition in Eq. (2.4) and arrived at Eq. (2.24):

$$G = \frac{\partial(F - U - E_c)}{B \partial a} \quad (2.24)$$

Thus, assuming that kinetic energy can be a mechanism for energy absorption in delamination tests at high strain velocity.

The kinetic energy of an ENF specimen has been analysed by Smiley and Pipes (Smiley and Pipes 1987). The authors found the term of the kinetic energy in the ERR calculation to be estimated with Eq.

$$\frac{\partial(E_c^{ENF})}{B\partial a} = -0.078\rho hu^2 \quad (2.25)$$

where ρ is the density of the material, h the half of height of the specimen and u the displacement imposed on the specimen. Using the CBT, the authors reached the ERR:

$$G_{II}^{ENF} = \frac{9P^2a^2}{16Bh^3E} \left(1 + 0.2 \frac{E}{G_{13}} \left(\frac{h}{a_0} \right)^2 \right) + 0.078\rho hu^2 \quad (2.26)$$

For another example, the CNF specimen the kinetic energy is written as follows (Maikuma, Gillespie and Wilkins 1990):

$$\frac{\partial(E_c^{CNF})}{B\partial a} = -0.633\rho hu^2 \quad (2.27)$$

For the CNF specimen, it was found that the terms of variation of the kinetic energy considered can be neglected because they represent only 1% of the total ERR. For the ELS specimen, Blackman et al. (Blackman, Dear et al. 1996) wrote the kinetic effects before and during crack propagation, however, for the speed of the tests, these effects account for less than 3% of the ERR, so they can be neglected.

Monitoring fracture location is one of the most difficult aspects of mode II testing because propagation happens quickly and without an obvious opening. Furthermore, due to microcracks in the relatively wide fracture process zone (FPZ), identifying the crack tip might be difficult (de Moura and de Morais 2008). This difficulty has led to develop several crack length measurement techniques (Schuecker and Davidson 2000, Blackman, Brunner and Williams 2006, De Moura 2008, Zabala, Aretxabaleta et al. 2015). One can use a high-speed camera with the help of marks to determine the crack length on each frame of taken by the camera. The other option is to use a crack gauge, where perpendicular gauge filaments of the bonded crack gauge are separated by a defined length, and during crack propagation, when the filament no longer produces resistance, it means it has been broken, and the new crack length can be saved (Liu, Nie et al. 2018). Figure 16 shows an example of a crack propagation gauge being implemented in a DCB specimen.

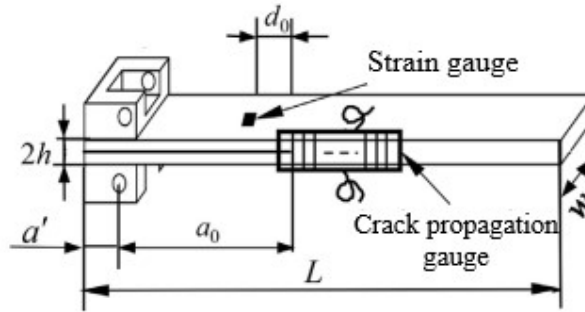


Figure 16 – Example of crack propagation gauge application in a DCB specimen.

2.3.1 Experimental Machines

The various specimens for delamination tests described in the previous section are performed utilising three major testing machines for dynamic testing (Zhao, Zhang et al. 2017). The Hopkinson bars, a servo-hydraulic machine and a weight drop machine.

2.3.1.1 Hopkinson Bars

To perform a dynamic compression test with Hopkinson bars (also known as the SHPB system for Split Hopkinson Pressure Bar or Kolsky bars), the sample is put between two long identical bars having a high elastic limit compared to the material examined. The two bars have strain gauges affixed to them. A projectile induces a longitudinal elastic wave of compression in the approaching bar, as Figure 17 illustrates. Part of this wave is reflected at the interface between the bar and the sample, while part is transferred to the sample and generates a wave in the bar. The waves velocities are calculated with:

$$V_e(t) = -c(\varepsilon_i(t) - \varepsilon_r(t)) \quad (2.28)$$

$$V_s(t) = -c\varepsilon_t(t)$$

where c is the velocity of the compression waves in the bars, and ε_i , ε_r and ε_t are, respectively, the "incident", "reflected" and "transmitted" deformation waves recorded at point A (for the first two deformations) and B (for the third deformation).

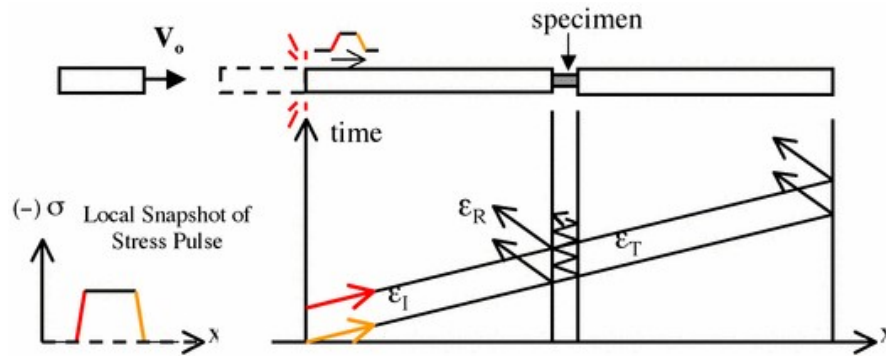


Figure 17 – Illustration of the SHPB experimental set up.

The advantage of this kind of experiment is the ability to recreate a dynamic impact by achieving relatively high projectile propulsion velocity.

2.3.1.2 Servo-Hydraulic Machine

This machine has the advantage of ensuring consistent deformation or loading speed throughout the test. Sensors are installed to gain access to data such as the force introduced and the acting displacement on the sensor. This test is mostly used to do quasi-static tests.

If the machine can perform relatively high velocity tests, usually up to 1 m/s of loading rate, it may be advantageous because data retrieval is simpler and more precise than with the other possibilities. It is the most widely used machine for the simplicity of its application.

2.3.1.3 Weight Drop Test

The goal of this type of test is to imitate an impact on a specimen placed below by dropping a mass from a known height. Knowing the mass of the falling object and the height from which it is dropped is essential in order to collect accurate data. Again, sensors are employed to collect the required information.

This test is appropriate for "intermediate" impact speeds. Indeed, the test is restricted by the height of the mass's launch, which in theory may be unlimited but is not in reality.

Since the falling object may bounce off the impacted specimen, the sensor results may be inaccurate unless an additional device is installed to prevent the rebound.

The acquisition of load values confirms a lack of precision during crack propagation since the signal oscillates substantially at high speed (Cantwell 1997). As a result, a drop tower is not suitable to be used in determination of the dynamic DFT.

2.3.2 Strain Rate (SR) Effect Review

Several writers have extensively researched the fracture of composite materials under static loading. Many experimental investigations are being conducted to better understand the behaviour of composite materials under dynamic loadings.

The basic mechanisms of the observed rate-dependent deformation and failure of composites are found to occur across multiple length and time scales. The contributing mechanisms are generally grouped as follows (Ma, Liu et al. 2021):

- Viscosity of composite constituents (polymer, fiber, and interfaces).
- The rate-dependence of the fracture mechanism as it is composed of many failure processes (e.g., fibre failure with fibre pull-out, matrix damage, and fiber-matrix interface failure) happening at the microscale level under different loading rates.
- Inertia effects include resistance to fast deformation, damage generation, and crack propagation. Micro-inertia effects can emerge as a result of wave reflection at the interfaces of constituents due to material heterogeneity.
- Thermomechanical dissipation is expected with higher loading rate as a shift from isothermal to adiabatic deformation and failure process.

The strain rate dependency of a brittle fracture type may also explain a decrease in DFT with increased loading rates. As shown in Figure 18, a brittle fracture can be expected to occur as a first approximation when the stress at the crack tip reaches a critical threshold that causes separation, σ_c . Material flow stress is strain rate dependent. If we approximate this deformation energy with the energy release rate of a material, we will have a larger area at lower strain rates. The mechanism for fracture initiation and propagation differs depending on the material in question.

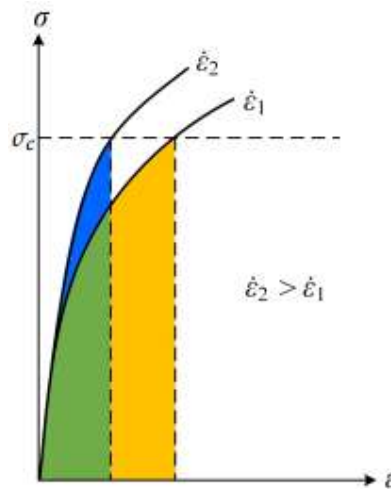


Figure 18 – Qualitative explanation of strain rate dependence of a brittle fracture.

Furthermore, when the crack tip is stationary, plastic flow can expand more freely, buffering the crack tip from the applied stress. The fracture is more brittle during crack propagation because the material does not have enough time to acquire plastic deformation. As a result, a more brittle failure type during crack propagation requires a lower energy release rate than a more ductile failure type during crack initiation. For example, in quasi-static testing, delamination is frequently dominated by fiber-matrix interface failure, but in dynamic tests, resin rich brittle fracture zones have been reported to be more dominating (Ma, Liu et al. 2021). De Moura (De Moura 2008) also investigated the failure modes in dynamic applications and reached the same conclusion. The author discovered that the size of the FPZ decreased with increasing strain rate.

However, the fracture energy can also increase as the loading rate increases. Experimental studies show that for a pure polymeric matrix with different propagation velocity levels, the crack surface roughness exhibits different characteristics because materials in the fracture process zone may experience high strain-rate plasticity, microcrack nucleation, thermomechanical interaction, and other complex deformation/failure mechanisms (Ma, Liu et al. 2021).

An overall understanding of results within the literature is necessary to comprehend if there is a consensus in the rate dependency of the DFT. Dynamic tests often give DFT values as a function of loading rate since these tests are commonly performed at constant loading rates. However, different strain rates at the crack tip are achieved while the crack propagates during a constant loading rate test, and so, some studies tried to define the DFT as a function of crack speed. Some studies use drop tower and don't mention the test's velocity. Although the interest of this thesis is mainly in Mode II, it may be useful to understand these effects in Mode I. Table 2 summarises some studies of the Strain Rate (SR) effect in this mode.

Table 2 – Summary of the literature in SR effect on DFT in Mode I

Study	Specimen	Material (Fibers/Matrix)	Loading Rate	SR dependency of DFT
(Guo and Sun 1998)	DCB	UD Carbon/ Epoxy	[1, 2] mm/s	No rate dependency
(Sun and Han 2004)	DCB	UD Carbon and Glass/Epoxy	[600, 800] m/s Crack Speed	No rate dependency
(Keshavanarayana and Nuggehalli Nandakumar 2009)	DCB	Prepreg Glass/Epoxy	[2E ⁻⁵ , 1.27] m/s	Decrease with rate
(Zabala, Aretxabaleta et al. 2015)	DCB	UD and Woven Carbon/Epoxy	[8.3E ⁻⁵ , 0.19] m/s	Decrease with rate (lower effect in woven)
(Thorsson, Waas et al. 2018)	DCB	UD Carbon/ Undisclosed	[10 ⁻⁶ , 0.06] m/s	Decrease with rate
(Liu, Nie et al. 2018)	DCB	UD Carbon/ Epoxy	[0.08, 30] m/s	Increase with rate after 10 m/s

Where UD means unidirectional laminate, and MD is for multidirectional laminate. Some remarks are given details to complete the information of this table. For example, Thorsson et al. (Thorsson, Waas et al. 2018) reported a decrease in DFT with loading rate that was associated with a decrease in fiber bridging.

Liu et al. (Liu, Nie et al. 2018) revealed that the primary fracture behaviour shifts from fiber-matrix interface debonding under quasi-static loading settings to epoxy matrix microbranching fracture under dynamix loading conditions, resulting in an increase in Glc.

This is also supported by Zabala's study (Zabala, Aretxabaleta et al. 2015), where the interlaminar fracture energy release rate was reduced by 19% for the woven composite and 31% for the UD laminate. This reduction has been linked to a change in crack growth behaviour from quasi-static to dynamic loading rates, which results in less fibre/matrix interface failure and more matrix brittle cracking in fractographic analyses.

Table 3 – Summary of the literature in SR effect on DFT in Mode II

Study	Specimen	Material (Fibers/Matrix)	Loading Rate	SR dependency of DFT
(Smiley and Pipes 1987)	ENF	UD Graphite/ Epoxy & PEEK	[4.2E ⁻⁶ , 9.2E ⁻²] m/s	Decrease with rate
(Compston, Jar et al. 2000)	ENF	UD Glass/ Vinylester	Drop Tower	No rate dependency
(Tsai, Guo and Sun 2001)	ENF	UD Glass/ Epoxy	[350, 700] m/s Crack Speed	No rate dependency
(Wiegand, Hornig et al. 2014)	ENF	MD Carbon/ Epoxy	[10 ⁻⁵ , 6] m/s	No rate dependency
(Adachi, Arai et al. 2000)	ENF	UD Carbon/ Epoxy	[10 ⁻⁶ , 10] m/s	Increase with rate
(Machado, Marques et al. 2017)	ENF	UD Carbon/ Epoxy	Unknown	Decrease with rate
(Yasaee, Mohamed et al. 2017)	ENF	MD Carbon/ Epoxy (zone with Z-Pins)	[1, 5] m/s	Increase with rate
(Kusaka, Yamauchi and Kurokawa 1994)	ENF	MD Carbon/ Epoxy	[10 ⁻⁵ , 10 ⁻¹] shear strain rate	Decrease with rate
(Li, Wang et al. 2021)	ENF	Carbon/Epoxy with carbon nanotubes	[8E ⁻⁶ , 6] m/s	Increase with rate
(Low, Johar et al. 2021)	ENF	UD Carbon/ Epoxy	[1.6E ⁻⁵ , 0.0083] m/s	Increase with rate

Study	Specimen	Material (Fibers/Matrix)	Loading Rate	SR dependency of DFT
(Maikuma, Gillespie and Wilkins 1990)	CNF	UD Graphite/ Epoxy & Graphite/PEEK	[0.01, 10] m/s	Decrease with rate
(Brambleby, Louca and Mouring 2017)	4ENF	MD Glass/ Vinylester	[10 ⁻⁵ , 0.1] m/s	Small increase with rate
(Zabala, Aretxabaleta et al. 2016)	4ENF	Carbon/Epoxy	[0.048, 0.19] m/s	Inconclusive (unconfirmed increase)
(Blackman, Dear et al. 1996)	ELS	UD Carbon/ PEEK	[1, 3] m/s	No rate dependency
(Colin de Verdiere, Skordos et al. 2012)	ELS	MD Carbon/ Epoxy	[0.1, 6] m/s	No rate dependency
(Guimard, Allix et al. 2009)	CLS	MD Undisclosed fiber and matrix	[0.5, 8] m/s	Increase with rate
(Tran 2011)	CLS	Carbon/Epoxy & Glass/Epoxy	[0.1, 12] m/s	Increase with rate
(Cantwell 1997, Berger and Cantwell 2001, Berger and Cantwell 2001)	DENF	UD Carbon/ Phenolic Resin	[10 ⁻⁶ , 3] m/s	Increase with rate

Particularly information about some individual studies is specified in the next paragraphs. Machado et al. (Machado, Marques et al. 2017) evaluated the strain rate and temperature dependence of the DFT of the material in study. The DFT at 20°C was calculated using three methods: ECM, CBT, and CBBM. The CBBM approach was adopted at the other temperatures, due to the difficulty of consistently monitoring the crack. The DFT values produced by the three methods were discovered to be quite similar.

Yasaee et al. (Yasaee, Mohamed et al. 2017) also used the ECM method, where he concluded that the kinematic effects were negligible. But, with a higher increase in loading rate (over 10 m/s), these effects should be considered.

Colin de Verdiere et al. Identified unstable crack propagation on the ELS specimen when the loading rate entered the dynamic range. Nonetheless, he identified that the crack velocity is positively related with the loading rate.

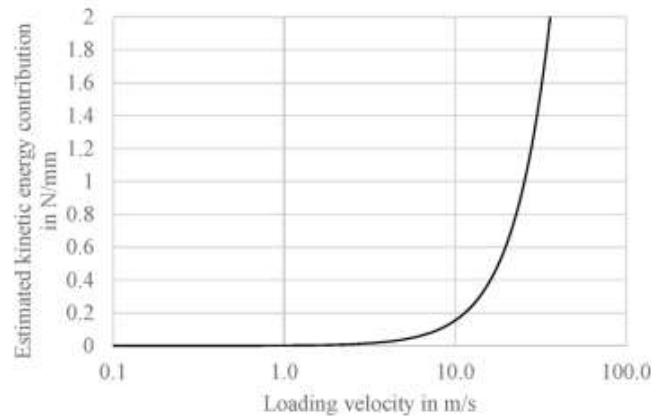
According to Guimard et al. (Guimard, Allix et al. 2009), under higher loading rate conditions, a certain amount of energy is no longer used to accelerate the main fracture in the same initial direction, but rather to generate additional microscopic crack surfaces at specific non-zero angles.

The concluding remarks from this literature review are reported in the next paragraphs:

Brittle fracture of the matrix is more common in dynamic settings, whereas fibre/matrix interface is more common in static settings because the crack has more time to find and propagate through the zone with more imperfections, such as voids and microcracks caused by the difference in strain between the fibres and the matrix. The difference between these two failure modes ERR that occur at different loading rates determines if the ERR will increase with rate (fibre/matrix interface ERR < brittle matrix cracking ERR) or decrease (fibre/matrix interface ERR > brittle matrix cracking ERR). Other factors that could contribute to this inconsistency are the test method, the loading rate, and the material itself.

Although the focus of this thesis is on 3D woven composites, there isn't a great deal of research in strain rate effects with 3D woven in Mode II delamination. This type of research is just starting to appear, focusing first on other properties such as elastic properties on 3D woven. And the purpose of this thesis is to fill in this lack of strain rate effect in Mode II delamination.

The kinetic energy that can be considered in the DFT for various specimens can be calculated, but since composites have a low density, static and low velocity tests can disregard it. Therefore, in this thesis, this effect won't be calculated because the maximum velocity to be tested is within the range of low velocity tests. Hahn et al. (Hahn et al., 2022) found the estimated kinetic energy contribution according to the loading velocity, and only below 10 m/s of loading rate, the kinematic effects can be neglected, as Graph 1 illustrates.



Graph 1 – Contribution of the kinetic energy of the DFT as a function of the loading rate.

2.4 Delamination Simulation

2.4.1 Static Models

2.4.1.1 Virtual Crack Closure Technique (VCCT)

In fracture mechanics, this approach is commonly utilised in delamination difficulties. VCCT assumes that the strain energy released when a crack grows by a given amount equals the strain energy necessary to close the crack of the same size (Magnus 2019). The other assumption is that a crack extension of a very small incremental length, Δa , does not meaningfully change the location of the crack tip. Looking at Figure 19, elements of length equal to Δa are used in a delamination problem, where the crack propagated from node i to node j .

The DFT is obtained by calculating the derivative of the strain energy according to the crack area. According to the theory, the strain energy stored in an elastic body equals one-half of the work done by the applied forces acting through the displacement boundary. By multiplying the forces at node j by the displacements at node i , the DFT may be calculated (Tabiei and Zhang 2018). This applies the second assumption and treats the displacement at node i as the same as the displacement at node j when the fracture tip advances to node k . Thus, using Eq. (2.29), the DFT for each mode is calculated.

$$G_I = \frac{1}{2\Delta a} T_i v_i$$

$$G_{II} = \frac{1}{2\Delta a} S_i u_i$$
(2.29)

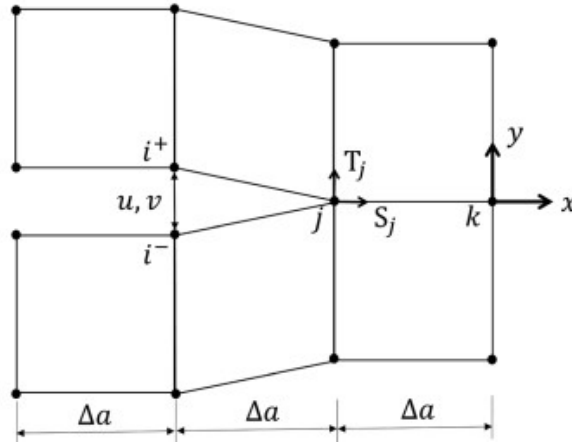


Figure 19 – VCCT forces and displacements of the nodes used to calculate the DFT.

Unfortunately, VCCT alone cannot predict where the initial crack begins. It requires a pre-existing crack to provide crack opening information to calculate the energy release rate. However, it can be used with some stress-based criteria, as shown in Section 2.2.1, to predict at what stress the crack initiates. Another drawback of VCCT is its limitation of capturing plasticity in a delamination process, as it is developed within the framework of LEFM, and so it doesn't simulate the FPZ. The VCCT method is very attractive for its ease of implementation.

2.4.1.2 Cohesive Zone Model (CZM)

The CZM is considered a two-parameter model that represents fracture initiation and propagation. The use of this powerful model in CFRP, initially developed by Barenblatt (Barenblatt 1962), has become increasingly popular. The two parameters that describe the fracture process are the DFT and the interlaminar strength. The DFT value is obtained from the delamination test under the appropriate mode of loading (i.e., mode I, II, III or mixed) and the interlaminar strength (which is the critical maximum value of the stress in the damage zone ahead of the crack) is attained from an independent test (Brunner, Blackman and Davies 2008).

A traction-separation curve is used to describe the fracture, with the area under the curve representing the DFT. The model is usually implemented using Finite Element Analysis.

These models establish the concept of a cohesive zone, as Figure 20 illustrates, in which the material has not totally lost its capacity to transfer load, but where the stress field at the crack tip causes a drop in the material's resistance owing to the start of damage.

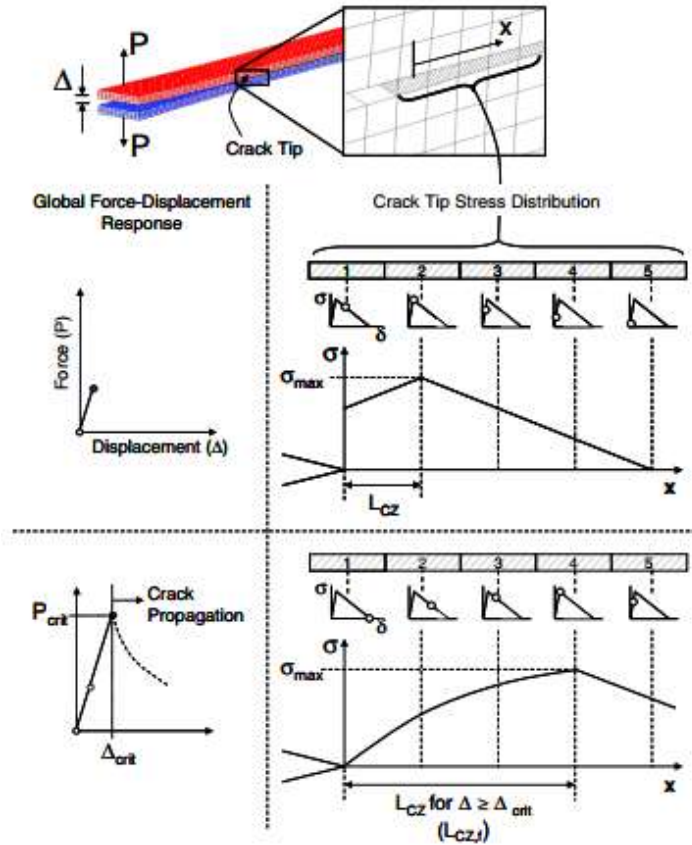


Figure 20 – Development of the numerical cohesive zone.

The key feature of this model is its ability to predict both onset and non-self-similar damage propagation without prior knowledge of the crack location and propagation direction, and without user input (Silva, de Moura and Morais 2006). Furthermore, it can also simulate the FPZ in front of the crack tip. Therefore, it overcomes the main disadvantages of the VCCT approach (Tabiei and Zhang 2018).

The start of the damaged phase is then at the peak when the stress is maximum, while the propagation phase only begins once the damage hits the max value of one. The FPZ is simulated by the number of elements that undergo damage.

A cohesive law uses a mixed mode stress-based criterion to control damage initiation, such as Eq. (2.2) defines, and an energy-based criterion to control failure (Tabiei and Zhang 2018). The possible delamination propagation criteria are reported in Table 1.

The initial slope of the CZM is defined as interface stiffness, K . This type of cohesive law with an ascending part is denominated as intrinsic law (Ortiz and Pandolfi 1999, Turon, Camanho et al. 2010). The extrinsic cohesive law, which does not have an ascending slope, requires a sophisticated algorithm to insert elements, and so the intrinsic law is the most used one.

Cohesive laws can also be categorized by their shapes (Abrate 2015):

- Polynomial law
- Exponential law (van den Bosch, Schreurs and Geers 2006, Zhang and Tabiei 2018)
- Bilinear law (Camanho and Dávila 2002)
- Trapezoidal law (Tvergaard and Hutchinson 1993), and so on, as Figure 9 illustrates.

Regardless of the cohesive law shape, they are all featured by some characteristic parameters like the interlaminar cohesive strength, critical ERR (or DFT), maximum separation, and so on. The bilinear law will be used to describe the CZM in this section, as it is the simpler model. The crack initiation and propagation criteria were discussed in a previous section. The quadratic stress criterion and the B-K law were selected as the favoured choice between the possible options. The CZM formulation in a finite element analysis will be described next.

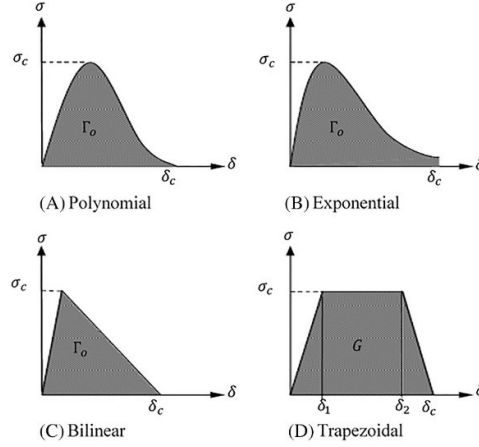


Figure 21 – Types of shapes of cohesive laws.

As simplification, the model considered will be in plain strain with a thickness of 1, meaning the strains are equal to the displacements, and the vector of relative displacement between two homologous nodes of an element (with a top and bottom face) is defined as:

$$\boldsymbol{\delta} = \begin{Bmatrix} \delta_I \\ \delta_{II} \end{Bmatrix} = \begin{Bmatrix} u_I \\ u_{II} \end{Bmatrix}_{top} - \begin{Bmatrix} u_I \\ u_{II} \end{Bmatrix}_{bottom} \quad (2.30)$$

Prior to damage initiation, the stresses, $\boldsymbol{\sigma}$, are attained through Eq. (2.31).

$$\boldsymbol{\sigma} = \mathbf{E}\boldsymbol{\delta} \quad (2.31)$$

where $\mathbf{E}$ is the diagonal matrix with the interface stiffness, K , that is inputted by the user (Silva, de Moura and Morais 2006, de Moura and de Morais 2008).

This equation is valid prior to the start of damage, which begins when the stress criterion is met. As a result, it is considered that damage onset is determined by stresses, but its evolution is determined by the DFT. To mimic the gradual damage at the fracture tip, a linear softening process between stresses and interfacial relative displacements is employed after the peak stress, where Eq. (2.32) defines the linear softening.

$$\boldsymbol{\sigma} = (\mathbf{I} - \mathbf{D})\mathbf{E}\boldsymbol{\delta} \quad (2.32)$$

This is accomplished numerically by including damage parameters whose values range from zero (undamaged) to unity (total loss of rigidity) as the material deteriorates. The zone ahead of the crack tip that undergoes damage is known the FPZ, as previously described.

The damage evolution depends on the law that is being used. For the simple bilinear law, the damage evolution is defined as:

$$d = \frac{\delta_f}{(\delta_f - \delta_0)} \left(1 - \frac{\delta_0}{\delta} \right) \quad , \quad \delta_0 \leq \delta < \delta_f \quad (2.33)$$

where d is the damage parameter for the complete mixed mode behaviour, δ_f is the displacement at failure, δ_0 is the displacement threshold where damage initiates, and δ is the acting displacement. When no mode index ($i = I, II$) is defined, the parameter relates to the mixed mode behavior.

The displacement threshold for each mode is simply calculated through the interlaminar strength and the interface stiffness:

$$\delta_0^i = \sigma_0^i \cdot K^i \quad , \quad i = I, II \quad (2.34)$$

The displacement at failure uses the DFT values and the area of a triangle using Eq.

$$\delta_f^i = \frac{2G_{ic}}{\sigma_0^i} \quad , \quad i = I, II \quad (2.35)$$

where G_{ic} is the DFT for each delamination mode.

The quadratic stress was used map the mixed mode damage initiation using:

$$\delta_0 = \delta_0^I \delta_0^{II} \sqrt{\frac{1 + \beta^2}{\delta_0^{II^2} + (\beta \delta_0^I)^2}} \quad (2.36)$$

where the mixed mode ratio, β is:

$$\beta = \frac{\delta^{II}}{\delta^I} \quad (2.37)$$

δ^{II} is the acting displacement in shear, while δ^I is the acting opening displacement, and they related to the total acting displacement using Pythagorean theorem:

$$\delta = \sqrt{\delta^I + \delta^{II}} \quad (2.38)$$

For mapping the mixed mode damage during propagation, the B-K law is used to develop Eq. (2.39) as described:

$$\begin{aligned} G_{Tc} &= G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \Leftrightarrow \\ \Leftrightarrow \frac{K \delta_0 \delta_f}{2} &= G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \Leftrightarrow \\ \Leftrightarrow \delta_f &= \frac{2}{K \delta_0} \left[G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \right] \Leftrightarrow \end{aligned} \quad (2.39)$$

Where the mixed mode ratio for the B-K law is related to β using Eq. (2.40).

$$\frac{G_{II}}{G_T} = \frac{K^{II} \beta^2}{K^I + K^{II} \beta^2} \quad (2.40)$$

Figure 22 displays the mapping defined up until now, in a traction-separation bilinear law.

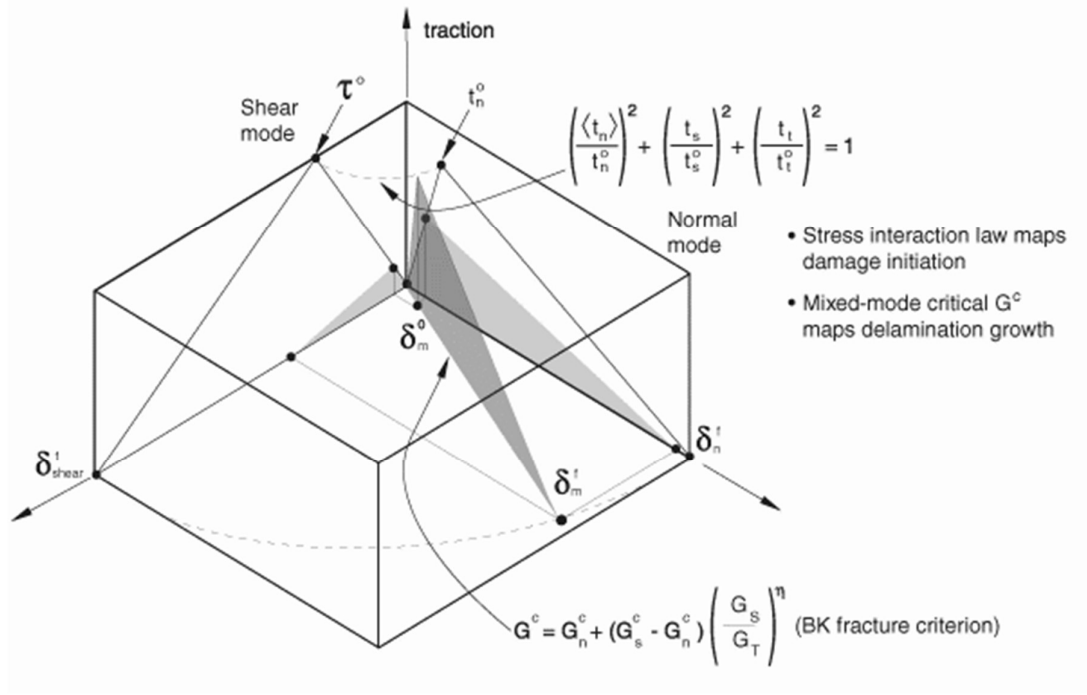


Figure 22 – Complete mapping of the CZM from ABAQUS.

Because there is a very small Mode III component at the specimen borders, the aforementioned mixed-mode damage model was employed joining the Mode II (direction 13) and Mode III (direction 23) with Eq. (2.41). Mode I is defined as direction 33.

$$\delta^{II} = \sqrt{\delta^{13} + \delta^{23}} \quad (2.41)$$

Liu et al. (Liu, Gu et al. 2015) investigated the influence of bilinear and exponential cohesive laws on composite laminate delamination behaviours. The results reveal that the form of the cohesive law has no significant influence on load response, except that the exponential cohesive law has greater convergence than the bilinear cohesive law. This is supported by the findings of Volokh (Volokh 2004) and Alfano (Alfano 2006), which studied the convergence between bilinear and trapezoidal law, and concluded that the bilinear cohesive law is simpler to implement, and still has a better convergence than the trapezoidal cohesive law.

The mix mode parameter, η , of the B-K law is chosen according to the mode I to mode II evolution along the coefficient G_{II}/G_T . This value can be obtained with the help of three tests. One for mode I, one for mode II and one for mix mode. A typical value is between 0.8 up to 2, depending on the experimental results, but can assume any real positive number.

The rest of the parameters that are necessary to implement correctly the CZM are the penalty stiffness, viscosity, the interlaminar cohesive strength and the DFT. The DFT can be obtained through the fracture tests, the interface strength can also be obtained through some tests, but is often assumed, since the difference in its value doesn't change much the cohesive behaviour (Alfano 2006). If only interface shear strength test such as the TAST is done, it is possible to assume the opening mode interface strength with this relation (Low, Johar et al. 2021):

$$\sigma_0^I = \sqrt{\frac{G_{IIc}}{G_{Ic}}} \cdot \sigma_0^{II} \quad (2.42)$$

This leaves the interface stiffness and the viscosity missing. The viscosity is usually attained with a Convergence Method, going from a relatively big value (around 0.1), and reducing the viscosity until convergence is met. The computational time is also considered in this Convergence Method in order to be within reason.

The interface stiffness however isn't a real physical parameter, and so its value can be tricky to decide on. The value of the interface stiffness must be high enough to hold the element faces together, avoid interpenetration, and to avoid artificial compliance from being defined into the model by the cohesive elements. The optimal interface stiffness is the highest value that does not cause numerical difficulties (Silva, de Moura and Morais 2006, Turon, Dávila et al. 2007, de Moura and de Morais 2008).

Turon, et al. (Turon, Dávila et al. 2007) assumed that if the through-thickness Young's modulus of the neighbouring sub-laminate, E' , is small enough in comparison to $K \cdot t$, the cohesive face will have no influence on the material's effective elastic characteristics. The thickness of the cohesive elements is t . As a result, the following equation is proposed to compute the interface stiffness:

$$K = \alpha \cdot \frac{E'}{t} \quad (2.43)$$

where the Young's modulus E' depends on the delamination mode, for example, E_3 for Mode I. The parameter α is larger than 1, and Turon et al. (Turon, Dávila et al. 2007) recommended considering $\alpha = 50$.

One unspoken consideration for a correct CZM is the Cohesive Zone Length (l_{cz}). Figure 20 already showed the existence of this parameter. This length is defined as the distance between the crack tip and the point of maximum cohesive stress (Moslemi and Khoshnavan 2015).

The length of the cohesive zone at the onset of crack propagation is unaffected by the applied load or crack length. This suggests that the length of the cohesive zone upon crack initiation is a material property (Turon, Dávila et al. 2007). There are several models in the literature that estimated the length of the cohesive zone. All of the models for estimation of the cohesive zone length have similar forms, resumed to Eq. (2.44) (Moslemi and Khoshnavan 2015):

$$l_{cz} = R E' \frac{G_{ic}}{\sigma_0^2} \quad (2.44)$$

R is a parameter that depends on each cohesive zone length model. The R values for each of these models are reported in the Table 4 (Turon, Dávila et al. 2007).

To accurately predict the propagation of delamination, an appropriate fine finite element discretization in the cohesive zone length is required to produce an adequate assessment of the interlaminar stress fields. The distribution of tractions ahead of the crack tip is not adequately represented when the cohesive zone is discretized by a small number of elements (Moslemi and Khoshnavan 2015). Thus, in order to generate effective FEM results, the cohesive zone length must contain a minimal number of components. The cohesive zone has the following number of cohesive elements:

$$N_e = \frac{l_{cz}}{l_e} \quad (2.45)$$

where l_e is the length of the cohesive element in the direction of the crack propagation.

There are numerous criteria for the minimal number of components in the length of the cohesive zone. This number, however, is not well established, ranging between 3 and 10.

In this work, 10 elements for the l_{cz} will be used to be sure that the cohesive zone length and the FPZ are well defined.

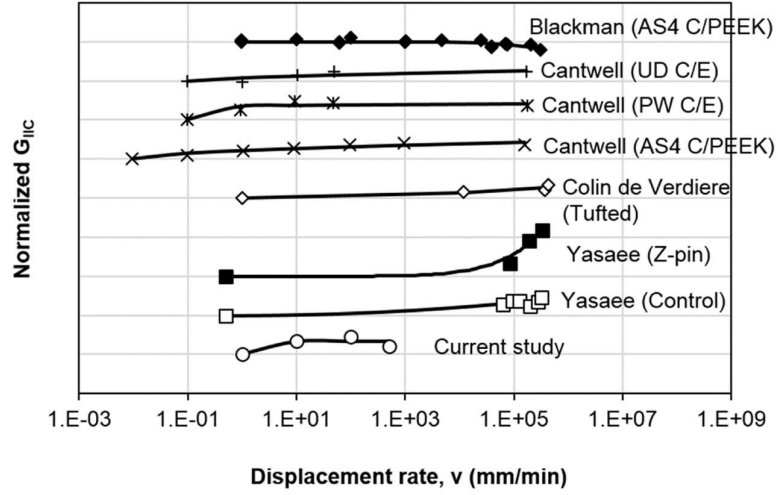
Table 4 – Length of the cohesive zone and equivalent value of the parameter R

Authors of the model	l_{cz}	R
Hui et al. (Hui, Jagota et al. 2003)	$\frac{2}{3\pi} E' \frac{G_{ic}}{\sigma_0^2}$	0.21
Irwin (Irwin 1957)	$\frac{1}{\pi} E' \frac{G_{ic}}{\sigma_0^2}$	0.31
Dugdale & Barenblatt (Dugdale 1960, Barenblatt 1962)	$\frac{\pi}{8} E' \frac{G_{ic}}{\sigma_0^2}$	0.40
Rice (Rice 1980), Falk et al. (Falk, Needleman and Rice 2001)	$\frac{9\pi}{32} E' \frac{G_{ic}}{\sigma_0^2}$	0.88
Hillerborg et al. (Hillerborg, Mod��er and Petersson 1976)	$E' \frac{G_{ic}}{\sigma_0^2}$	1.00

2.4.2 Dynamic CZM for Strain Rate Effects

Low et al. (Low, Johar et al. 2021), besides their open study, retrieved the normalized DFT in Mode II according to the loading rate of some studies cited in Table 3 in Graph 2.

This type of graph can be used to simulate the SR effect in the delamination using a numerical model. Inserting a CZM between laminae with an adequate cohesive law is a popular approach for dealing with delamination in composites. However, rate-independent cohesive interface parts are incapable of capturing the key characteristics of a composite's dynamic delamination process (Ma, Liu et al. 2021). A fit curve can be applied to a graph with DFT or interlaminar strength according to the strain or loading rate, for example Graph 2, and then introduced in a numerical analysis with a User Material (UMAT) or Vectorized User Material (VUMAT) for a CZM, where these two properties change according to the loading rate specified. The difference between the UMAT and VUMAT is the formulation employed in the solver, which are the standard/static and explicit, respectively.



Graph 2 – Normalized DFT in Mode II vs Loading rate of some studies reported in Table 3.

Usually, the fit curve that defines the aforementioned graph results in a semi-logarithmic equation, as Eq. (2.46) displays (Li and Wei 2020, Low, Johar et al. 2021, Rezasefat, Amico et al. 2022).

$$\frac{G_{IIc}(\dot{u})}{G_{IIc}^{ref}} = 1 + m \left[\ln \left(\frac{\dot{u}}{\dot{u}_{ref}} \right) \right]^\zeta \quad (2.46)$$

For a more complete model to represent the rate-dependent behaviour, May (May 2015) developed a CZM in which the maximum stress and fracture energy of both mode I and mode II loading were relying on the strain rate of the cohesive elements. The rate dependency was introduced for both the cohesive strength and the fracture energy of independent modes with a Johnson–Cook law:

$$\sigma_0^i(\dot{u}^i) = \begin{cases} \sigma_0^{i,ref} \cdot \left(1 + C^i \cdot \log \left(\frac{\dot{u}^i}{\dot{u}_{ref}^i} \right) \right) & \text{for } \dot{u}^i \geq \dot{u}_{ref}^i \\ \sigma_0^{i,ref} & \text{for } \dot{u}^i < \dot{u}_{ref}^i \end{cases}$$

$$G_c^i(\dot{u}^i) = \begin{cases} G_c^{i,ref} & \text{for } \dot{u}^i < \dot{u}_{ref}^i \\ G_c^{i,ref} \cdot \left(1 + m^i \cdot \log \left(\frac{\dot{u}^i}{\dot{u}_{ref}^i} \right) \right) & \text{for } \dot{u}_{ref}^i \leq \dot{u}^i \leq \dot{u}_{inf}^i \\ G_c^{i,inf} & \text{for } \dot{u}^i > \dot{u}_{inf}^i \end{cases} \quad (2.47)$$

where $i = I, II$ for each delamination mode. C^i and m^i are rate-sensitivity constants, $\dot{u}^i$ is the displacement jump rate; $\dot{u}_{ref}^i$ is a reference displacement jump rate.

To attain these experimental values ($C^i, m^i, \sigma_0^{i,ref}, G_c^{i,ref}, G_c^{i,inf}$) it is required an extensive study on various tests at different displacement rates, which is impossible for the material available, so some assumptions will be made for these quantities.

There are more complex methods that can be employed, but the incorporation of Eq. (2.47) within a UMAT can successfully simulate the rate effect of cohesive elements to predict the strength of a structure.

The choice between UMAT and VUMAT formulations depends on the specific simulation requirements. VUMAT uses the explicit solver for scenarios with low velocities and dominant kinematic effects but may struggle with higher precision and stability problems.

UMAT uses the standard solver, employing the Jacobian matrix for convergence and providing more accurate results. It is versatile, as it can be integrated into dynamic implicit formulations for mass introduction, making it suitable for a wider range of simulations.

While VUMAT excels in high-velocity impacts, UMAT is the preferred choice for simulations demanding precision, stability, and versatility. Its ability to handle SR or dynamic implicit formulations and deliver more accurate results makes it the preferred formulation.

3 Test Campaign

3.1 Materials

Two plates of 500x500 mm of the 3D woven composite previously manufactured were provided for interlaminar fracture testing. One of the plates has with a centred Teflon insert in the warp direction, and a second in the weft direction. The material specification is confidential; thus, images or material properties will not be shown. An additional plate of 500x500 mm plate was provided to study other material attributes such as interlaminar shear strength. Depending on the direction of the samples, the specimens can be in the warp and weft directions. The elastic material properties of the material were also provided to be used in the numerical models for both warp and weft directions. These properties aren't displayed for confidentiality reasons.

The warp, weft, and thickness direction will be numbered 1, 2, and 3, respectively.

The objective of this test campaign is to capture the delamination behaviour of this material, particularly in Mode II. This requires a selection of the appropriate tests to reach the necessary material properties to be inserted in a CZM to predict this behaviour with a numerical model. Hence, the measured properties are the interlaminar shear strength and the DFT in Mode II. The next subsection will focus on the selection of the specimens to use in the test matrix.

3.2 Test Matrix

The goal of the experimental campaign is the characterisation of the material's cohesive law. Hence, a selection of tests was defined, starting with the tests loading speed, which will be the same for the interlaminar shear strength and Mode II DFT tests.

3.2.1 Test Speed and Test Types

The choice of the implementation and the displacement velocities need to be selected.

First, drop tower is directly ruled out because it does not guarantee a clean and reliable data reading due to possible bounces that can cause oscillations in the signals. Thus, the choice is between the Hopkinson bars, if it is needed high enough loading rates, and the hydraulic machine for static and up to 1m/s loading rate (max rate of the machine Instron 5900R).

From the literature, the articles that use extremely high loading rates use drop tower, while for lower velocity loading rates it's used Hopkinson bars or the hydraulic machine. Since the main difficulties in the aeronautical industry with composites are due to low velocity

impacts that could occur during manufacture and maintenance, loading rates around 1 to 4m/s are enough to understand the dynamic effects of the material in analysis (Richardson and Wisheart 1996). At these lower speeds, hydraulic machines are more precise than Hopkinson bars are guarantee reliable results.

Although studying up to 4m/s (max velocity of a tool in free fall from a height of 1m) is in the interest of the objective, due to the limitation of the hydraulic machine to be used in the experiments, the max velocity was set at 1m/s. Another advantage to impose this max velocity is that at loading rates above about 1 m/s aren't so influenced by the kinematic effects, reducing them to negligible values (Blackman, Kinloch et al. 1996, Hahn, Channammagari et al. 2022), as seen in Graph 1. So, the choice of test velocity was in between static and 1 m/s. Since there isn't enough material, only three tests at the max and minimum velocity were planned. Due to time constrains, only the static tests were made. However, the planned dynamic tests will also be explained for the sake of completeness.

Ideally, the mode II crack resistance curve and interlaminar shear strengths would have been measured in

- static and dynamic (1m/s) conditions
- warp and weft directions.

However, due to time constrains, only the static tests in the warp directions (and in the weft directions for the interlaminar shear strength) were done in this thesis, since warp direction is one of the most used in the literature. The remaining samples were prepared but will be tested in the future.

3.2.2 Interlaminar Shear Strength Tests

The Thick Adherend Shear Test (TAST) was used to determine the interlaminar shear strength in Mode II and Mode III, using warp and weft direction, respectively.

Inspiration from the dimensions of a test conducted at Safran to size the specimens and from (Banea and Silva 2009), as Figure 23 shows. From these dimensions, it is necessary to check that the test is indeed a shear test and that the peel stress is negligible.

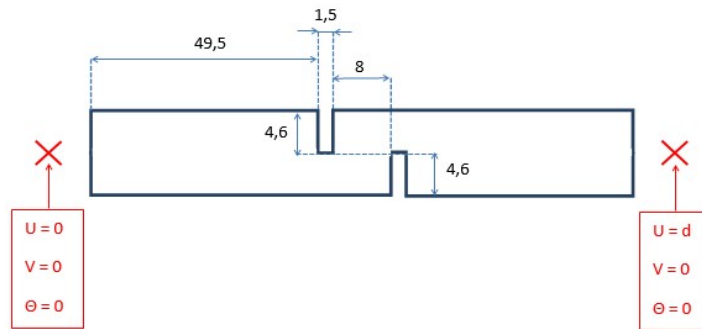


Figure 23 – TAST specimen dimensions.

3.2.2.1 Data Reduction Method (DRM)

In this specimen in particular, the only analytical value obtained from the results is the interlaminar shear strength, which is simply estimated with Eq. (3.1) for Mode II retrieved from warp direction TAST, and Eq. (3.2) for Mode II retrieved from weft direction TAST (Althof and Neumann 1974). As a result of coordinate axis rotation, for a weft direction test, Mode II shear strength is the τ_{zy} value while τ_{zx} is used for Mode III shear strength.

$$\tau_{zx} = \frac{P_{Failure}}{b * L} \quad (3.1)$$

$$\tau_{zy} = \frac{P_{Failure}}{b * L} \quad (3.2)$$

From the DIC data, it is also possible to obtain the Stress vs Strain curve of the failure plane between notches, which the initial slope directly relates to the shear modulus. This can be compared to the material data given, for additional confirmation.

In the TAST, specimens tested in the warp direction have usually failed completely at the end of the test, while for the specimens in weft direction some fibers don't fully break keeping the specimen halves connected after the test. The wave effect of the fibers in a 3D woven material could create these and other effects.

3.2.3 Crack Resistance Curve Tests

There are several tests that are used to determine the DFT for Mode II in composite materials including: ENF, ELS, 4ENF, CLS, CNF, INF, TCT, and DENF tests.

The goal is to obtain the crack resistance curve (R-Curve) of the material under static and dynamic conditions using the plates available. For this reason, it is necessary that:

- the test standard allows for samples that can be made from the available plates (which invalidates the use of the CNF, INF, DENF and TCT geometries).
- the crack propagation is stable under static and dynamic conditions.
- the largest possible crack length for a more complete R-Curve.

And ideally:

- no additional rigs need to be manufactured.
- Experience in testing these samples exists within the team.

So, the four remaining possible specimen geometries are the ENF, ELS, 4ENF, and CLS.

The benefits and drawbacks of each possible test are shown in the Table 5.

Table 5 – Possible tests advantages and disadvantages

Test	Advantages	Disadvantages
ENF	Standardized static test	Unstable crack propagation
	Standard specimen	Low crack propagation length for stable test
	Easy set up to mimic	Non-constant crack growth rate
ELS	Standardized static test	Complex assembly due to sliding embedding and additional specimen handling with load introduction part
	Standard specimen	Possibility of propagation instability of crack in dynamics (Blackman, Dear et al. 1996)
	Stable with the $a/L > 0.55$ condition	Non-constant crack growth rate
		Large deflection led to cracks out of the desired crack path
4ENF	Standard specimen	Additional assembly parts (for correct load distribution)
	Quasi-constant crack growth rate	Difficulty of dynamic assembly
	Stable and large crack propagation	Friction effect not negligible ((Martin and Davidson 1999, Wang, Nakata et al. 2009, Parrinello 2018, Liu and Chen 2019), but if compliance and crack length correctly measured, it's an appropriate DFT test (Schuecker and Davidson 2000))
CLS	Exploratory	Additional mounting to avoid Mode I (optional), without, it is a mixed mode I+II behaviour
	Stable and the longest crack propagation	Non-standard sample so additional manipulations to be planned (machining, gluing of tabs, etc)
	Quasi-constant crack growth rate	

Since only the CLS and 4ENF are stable regardless of the of the test speed and throughout their entire behaviour, these are the primary tests selected. CLS test was used in a mixed-mode behaviour to reach the B-K law parameter, even though it is possible to have a pure Mode II behaviour, hence, the CLS test had no extra mounting. The ELS will also be planned to confirm the 4ENF results, thus confirming if the friction effect can be ignored.

The 4ENF and ELS tests have been done within the ISAE-Supaero lab, so the specimen mounting already exist, as for the CLS test is a simple tensile test.

Table 6 concludes the test choice, with the planed tests outlined. Due to lack of time, the remainder of the test, especially the dynamic ones, were not able to be done, but will be finished in the continuation of this work. The number of tests performed is also reported in this table.

Table 6 – Number of static tests performed within the test campaign

Tests	TAST Warp	TAST Weft	4ENF	CLS (mix mode I+II)	ELS
Planned N° of tests	3 Static	3 static	3 Static	3 Static	3 Static
	3 Dynamic	3 Dynamic	3 Dynamic	3 Dynamic	3 Dynamic
N° of tests done	3 static	3 static	3 static	1 static	None

3.2.4 DRM and Sizing of the Delamination Tests

Many DRM models have been proposed and are present in the form of analytical formulas ready to be used in order to determine the DFT, as seen in Section 2.2.4.

These models have the advantage of being simple to implement and producing results based on an algebraic solution. However, the reliability is impacted by the simplifying assumptions used to reach the solution.

The Experimental Compliance Method is the most accurate way for determining toughness from 4ENF, CLS and ELS test data. That is, beam-theory data reduction techniques have been found to create errors in DFT as measured by mode II bending tests. These inaccuracies occur mostly owing to the difficulty in precisely determining the flexural stiffness of each test specimen. ECM is a direct data reduction method that solely considers linear elastic behaviour and self-similar crack advance. As a result, any errors caused by uncertainty in each test specimen's geometric or material qualities are avoided. (Schuecker and Davidson 2000).

Hence, the simple objective of these data reduction methods is, first, to obtain a single value of DFT to input in the numerical models, secondly, to arrive at the compliance equations to know the expected power of the compliance vs crack curve to apply the ECM, finally, to check the stability of the crack propagation. From what was found in the literature, SBT is sufficient for the objectives outlined.

To conclude each subsection, the final geometry of the different specimens is illustrated.

3.2.4.1 4ENF Test

For the 4ENF samples, the load is applied through rollers to a loading platen to which the loading pins are connected. This permits the loading platen to freely spin about an axis perpendicular to the length of the specimen and guarantees that both loading pins transmit the same amount of force onto the specimen. To prevent uneven stress over the width of the specimen, the support pins are designed to be able to rotate about an axis parallel to the specimen's length. The inner span is located in the middle of the outer support rollers.

The SBT to reach the analytical equation for the 4ENF sample DFT it is not an easy task. Martin and Davidson (Martin and Davidson 1999) were able to develop the analytical equation, Eq. (3.3), and also the displacement control solution, which is important to arrive at the verification of the stability of the crack propagation. The thickness of the specimen is $2h$, and the rest of the dimensions defined by Martin and Davidson can be seen in Figure 24.

$$G_{II}^{4ENF} = \frac{9}{4B^2h^3E} \left[P_L S_L \left(1 - \frac{a}{2L} \right) + P_R a \left(1 - \frac{S_R}{2L} \right) \right]^2 \quad (3.3)$$

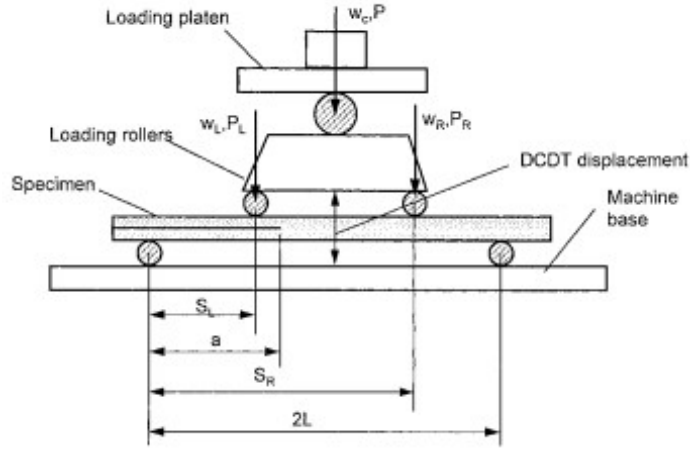


Figure 24 – 4ENF set up with dimensions to reach the analytical solutions (Martin and Davidson 1999).

The assumptions the authors followed were that the configuration was symmetric, meaning that $S_L + S_R = 2L$ and the test, being in a pinned configuration, which denotes that the loading platen can freely rotate, making it is possible to say that $P_L = P_R = P/2$ and $w_L + w_R = 2w_c$. Substituting these in Eq. (3.3) it is possible to arrive at Eq. (3.12).

$$G_{II}^{4ENF} = \frac{9P^2L^2}{64B^2h^3E} \quad (3.4)$$

Then it is necessary to check the stability of the crack propagation. As seen in Section 2.2.2, the following condition needs to be met, Eq. (3.13), since G_c is considered a constant of the material, the derivative must be negative for stability.

$$\frac{\partial G(a)}{\partial a} < \frac{dG_c(a)}{da} = 0 \quad (3.5)$$

From the force and displacement assumptions, the compliance C is written as in Eq. (3.6):

$$C^{4ENF} = -\frac{w_c}{P} = -\frac{w_L + w_R}{2(P_L + P_R)} \quad (3.6)$$

Martin and Davidson reached the equations that define the deflections of the left and right loading rollers. Inserting these in Eq. (3.6) it is possible to arrive at the compliance of the system:

$$C^{4ENF} = \frac{L^3}{32Bh^3E} \left(1 + \frac{9a}{L} \right) = C_0 + C_1 \cdot a \quad (3.7)$$

Changing from a force control to a displacement control, the DFT is changed to Eq. (3.8).

$$G_{II}^{4ENF} = \frac{9w_c^2L^2}{64B^2h^3E(C_0 + C_1a)^2} \quad (3.8)$$

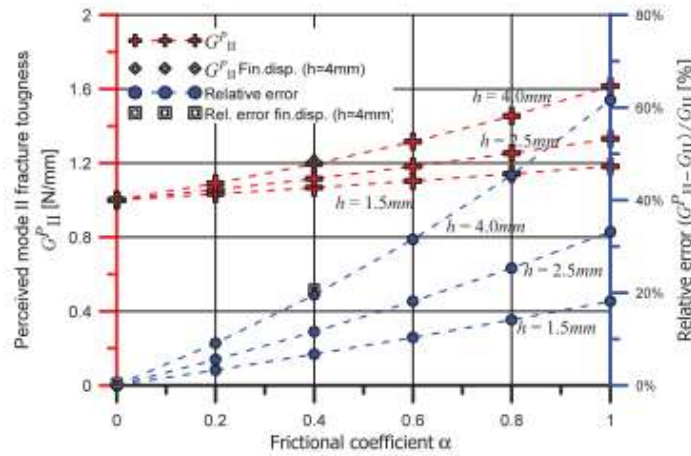
With some manipulation, it is possible to arrive at Eq. (3.9), which is always negative, since all the variables are positive, concluding that the 4ENF sample has always stable propagation under displacement control.

$$\frac{\partial G_{II}^{4ENF}}{\partial a} = \frac{9w_c^2 L^2}{32B^2 h^3 E} \cdot \frac{-C_1}{(C_0 + C_1 a)^3} \quad (3.9)$$

From a previous work, two “Short” samples of 4ENF with a total length of 120 mm were already cut and their static test was performed. The objective of these two samples was: checking possible friction or size effect of this geometry and mature the experimental procedure.

However, Parrinello (Parrinello 2018) did an extensive study on the frictional effect of the material surfaces on the calculation of G_{IIc} in the basis of the classic Euler-Bernoulli bending beam theory. The analysis on the thickness and frictional coefficient was done using numerical and analytical analysis, where it was found that the higher the friction between surfaces, the higher the error to the perceived G_{IIc} , and also that with increase in thickness in relation to the length of the specimen, an higher error to the perceived G_{IIc} is also obtained, Graph 3 (Parrinello 2018).

With this conclusion, with the material plate having a big thickness, it is preferable to utilise a specimen with the biggest length possible, within the sizes of the plate of course, in order to reduce the frictional effect. So, the final dimension of the 4ENF specimen is seen in Figure 25.



Graph 3 – Frictional effect on the relative error of DFT of a 4ENF test with a length of 100 mm.

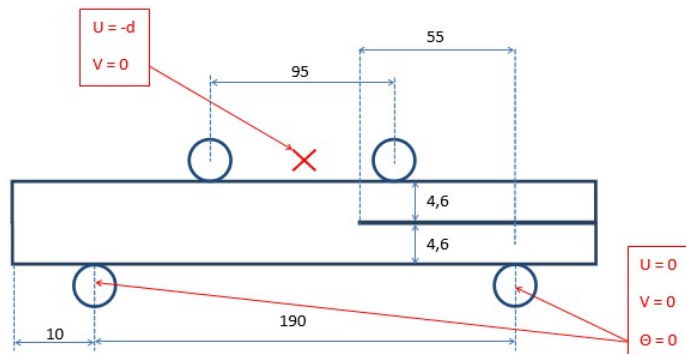


Figure 25 – Long 4ENF dimensions.

3.2.4.2 CLS Test

From the specimen design, this test is a simple tensile test, so the use of the energy of deformation to arrive at the DFT with the definition established in Section 2.2.2 and using the Castigliano's theorem is sufficient. Guimard et al. (Guimard, Allix et al. 2009) assumed the rotation due to the unsymmetrical load P negligible, meaning that the elastic bending energy is approximately zero, and this lead to good analytical results. The unsymmetrical load effect is also diminished by adding the part at the loading region in order to input the load at the centre thickness of the specimen. Figure 26 shows a typical stress analysis of the CLS specimen.

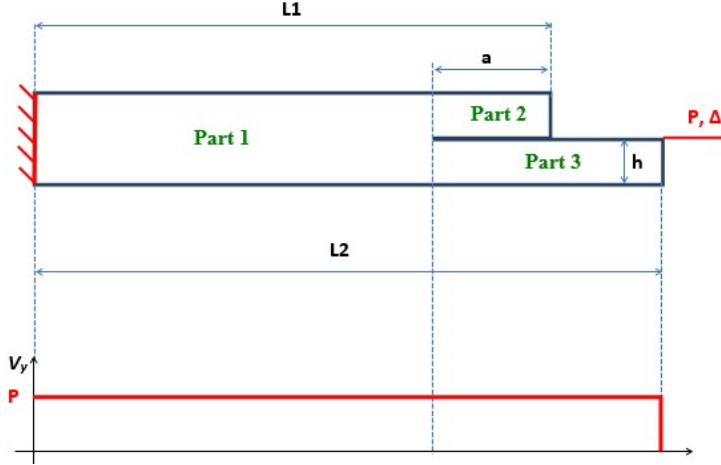


Figure 26 – CLS specimen drawing with stresses and moments of each beam part.

Part 2 of the specimen isn't suffering any load, so no elastic energy exists in this part. The stress shown in Figure 26 are only for Part 1 and Part 3 that suffer tensile deformation, where its energy can be calculated with:

$$E_{el} = \iint \frac{\sigma^2}{2E} dA dL \quad (3.10)$$

where V_y is the stress from the traction force, $V_y = P/BH$, A is the area of the cross section, which is equal to the width time the thickness of the beam in question, and L is the length of the beam. In order to simplify, the thickness of the specimen is $2h$ and Part 2 and 3 have half of the thickness, h .

The length of Part 1 is $(L_1 - a)$, while Part 3 is $(L_2 - L_1 + a)$.

The tensile force for Part 3 is equal to P for the whole length, which is also transferred to Part 1. The difference in stress is solely from the difference in thickness, from h in Part 3, to $2h$ in Part 1.

The sum of the energies of all part equates at the total elastic energy, Eq. (3.11).

$$E_{el_{total}} = E_{el_{P1}} + E_{el_{P3}} = \frac{(L_1 - a)P^2}{4BhE} + \frac{(L_2 - L_1 + a)P^2}{2BhE} \quad (3.11)$$

Using Castigliano's theorem, the compliance is arrived with:

$$C = \frac{\delta}{P} = \frac{1}{P} \frac{\partial E_{el}}{\partial P} = \frac{(L_1 - a)}{2BhE} + \frac{(L_2 - L_1 + a)}{BhE} \quad (3.12)$$

From the DFT definition:

$$G_{I+II}^{CLS} = \frac{P^2}{2B} \frac{\partial C}{\partial a} = \frac{P^2}{4B^2 h E} \quad (3.13)$$

For the stability check, it is necessary to change to a displacement control DFT equation. Identical to the 4ENF sample, the compliance is linear with the crack length, so the C_I and C_0 can be identified, Eq. (3.14).

$$C = C_1 a + C_0 = \frac{1}{2BhE} a + \frac{2L_2 - L_1}{2BhE} \quad (3.14)$$

The DFT with displacement control is calculated through Eq.

$$G_{I+II}^{CLS} = \frac{\delta^2}{4B^2 h E} \frac{1}{(C_1 a + C_0)^2} \quad (3.15)$$

And the derivative is arrived at Eq. (3.16):

$$\frac{\partial G_{I+II}^{CLS}}{\partial a} = \frac{\delta^2}{2B^2 h E} \frac{-C_1}{(C_1 a + C_0)^3} \quad (3.16)$$

If $(C_1 a + C_0) > 0$, this means that the CLS specimen is always stable since Eq. (3.16) would always be negative. From Eq. (3.14) we can arrive at Eq. (3.17)

$$a + 2L_2 - L_1 > 0 \Leftrightarrow a > L_1 - 2L_2 \quad (3.17)$$

Knowing that $L_2 > L_1 > 0, a > 0$, Eq. (3.17) is always true, concluding on the stability of crack propagation of the CLS specimen.

The CLS sample was set also to the biggest size possible, in order to obtain the biggest potential crack length, Figure 27.

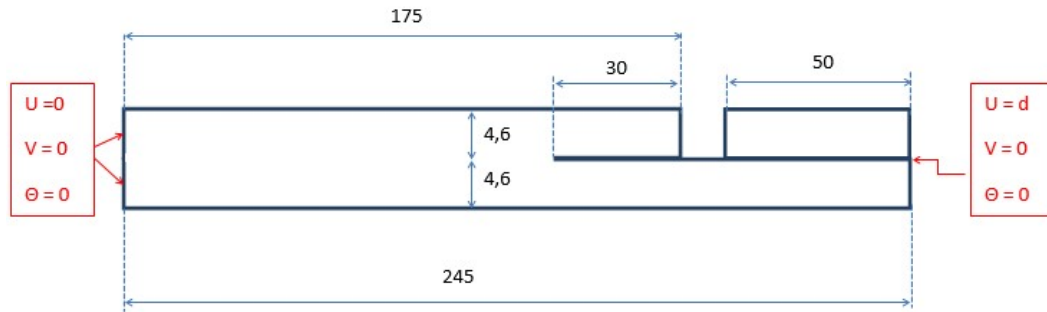


Figure 27 – CLS specimen dimensions.

3.2.4.3 ELS Test

Blackman and Williams (Blackman, Brunner and Williams 2006) arrived at DFT equation for the ELS specimen, and the energy analysis is reported in 0.

In their study they referenced the large displacements correction factor, F , and the correction factor to account for the bonded-on end-block effect, N . Another difference from other authors is the Δ_{clamp} , where in this study will be half of the clamped region. The clamp itself doesn't encastre the specimen, since it can move in the longitudinal direction, but the moment that fixes the rotation of the specimen needs to be defined in the centre of the clamp, and not at the end of the clamp, Figure 51 of the 0.

The DFT equation, compliance equation and the stability function obtained are in Eq. (3.18), (3.19) and (3.20), respectively.

$$G_{II}^{ELS} = \frac{9P^2 a^2}{4B^2 h^3 E} \quad (3.18)$$

$$C = \frac{3}{2Bh^3 E} \left(a^3 + \frac{(L + \Delta_{\text{clamp}})^3}{3} \right) \quad (3.19)$$

$$\frac{a}{(L + \Delta_{\text{clamp}})} > \frac{1}{\sqrt[3]{6}} \approx 0.5503 \quad (3.20)$$

For the ELS specimen to have stable propagation, the crack length needs to be at least 55% of the length of the specimen plus half of the clamp region length.

3.3 Specimens Cutting and Preparation

All of the part drawings for the different specimens that were used to cut and prepare them are in Annex A, where Figure 47 of A.1 is the TAST specimen, Figure 48 of A.2 is the Long 4ENF specimen, Figure 49 of A.3 is the CLS specimen, and Figure 50 of A.4 is the ELS specimen. The latter was not cut due to lack of time.

The plate without the Teflon film was cut to make the TAST specimens, for both warp and weft direction. For the 4ENF, CLS and ELS specimens, the plate in warp direction with the Teflon insert will be used.

The specimens were cut using a rotating blade, to get a clean cut. The indents in CLS and TAST specimens were obtained with the help of an abrasive cutting wire.

The CLS and TAST specimens required bonded tabs to be incorporated. The tabs were made out of glass and epoxy composite. Before the speckle pattern is painted, the specimens were sanded by hand cleaned with acetone, and then the tabs were bonded with Araldite 2015-1, with the thickness of the layer being 0.2mm. Then the specimens were held to a non-adhesive part until the bonded layer was dry, as seen in Figure 28.



Figure 28 – TAST specimens adhesive drying after the application of the bonded tabs.

A speckle pattern is necessary to perform Digital Image Correlation (DIC) analysis, and so, one day before the tests, each specimen was painted on the side with a white paint, dried for two hours, to obtain the background for the speckles, which were then splattered with a spray black paint from a far to obtain the desired pattern, as Figure 29 demonstrates. The

pattern needs to be as uniform as possible, so that the DIC analysis doesn't increase the projection error, which leads to misleading displacement and strain data.



Figure 29 – Specimens preparation: Application of white paint in TAST specimens, then the speckle pattern in a CLS specimen.

After the 4ENF, CLS and ELS specimens are dried, a crack gauge was bonded to the not speckled side face of the specimens. The first filament of the gauge was on top of the crack tip. To find the crack tip a microscope (VHX Digital Microscope) was used.

3.4 Experimental procedure

The displacement-controlled loading was applied to the specimens via the Instron 5900R in the ISAE-Supaero Département Mécanique des Structures et Matériaux (DMSM) Static laboratory, with a 50 kN load cell for all the tests, except the CLS where the 100 kN load cell of the machine was used. The Instron actuator moves down or up to load or unload the specimen.

The final system to be used in the 4ENF, CLS and ELS is the crack gauge, which uses two different crack gauges bonded in series. When the crack propagates, it breaks the gauge filaments and cause a difference in resistance which is recorded alongside the displacement and force data. Knowing the distance between the filaments and the distance between the two crack gauges, it is possible to retrieve crack vs displacement points.

The speckle dots within the DIC system discretize the face of the specimen comparable to nodes in a finite element model (Magnus 2019). The cameras are placed on the front side to obtain the displacement field and for further comparisons between experimental and numerical results, using 2 CDD cameras with a 4 M pixels resolution with a maximum frequency of 5 Hz, analysed using the Vic3D© commercial software.

The two short specimens of the 4ENF test won't use crack gauges and were only utilised to investigate the 4ENF set up and look for possible errors that could occur. The number of tests that were performed during the test campaign is listed in Table 6. Due to lack of time no more experiments were performed.

The order of the procedure is: the DIC system was calibrated according to the testing guide (Correlated-Solutions 2016). Figure 30 shows an example of a calibration image. Then the specimen was placed with the help of calibrated ruler to be sure that the specimen is placed in the right position and direction. To start each test, both the Instron and the DIC were zeroed, the data recording was started, then the loading was started. The number of images per second of each test varied, which directly influences the amount of data acquired. After each test was completed (the specimen was completely unloaded) the data recording was stopped, and the data was saved. Then the DIC analysis were performed, where the subset

and step values. The first behaves alike the finite elements, and the second is the definition (number of pixels) that the analysis will measure. The minimum size of the squares created by the subset needs to be big enough to encapsule the larger speckle the specimens have, and the smaller the values of these variables, the more precise the analysis is, at the cost of computational time. Thus, for each speckle pattern, the minimum possible values were selected.

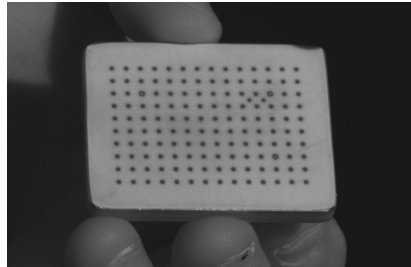


Figure 30 – Example of a calibration image with 14x9 (3mm) calibration target.

In Figure 31a 4ENF sample is shown as an example of the DIC system, crack gauge and hydraulic set up for the experiment. The CLS and the TASTs were simple tensile tests, where grips connected to the machine held the specimens, the DIC and crack gauge for the CLS set up were the same as seen in Figure 31.

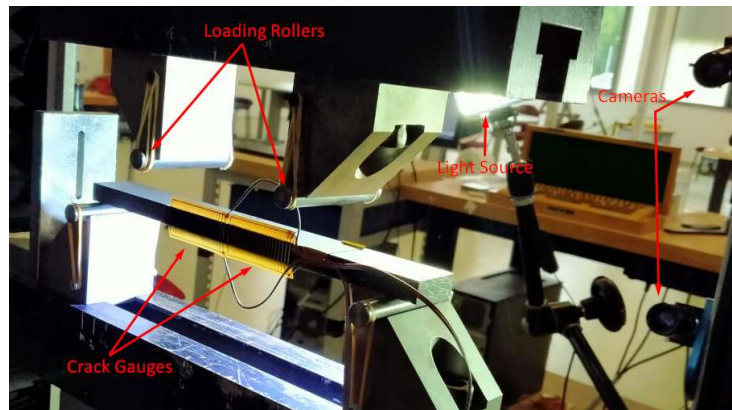


Figure 31 – 4ENF specimen set up.

3.4.1 DIC Measurements and Postprocessing

To have correct compliance measurement, it is necessary to confirm that the machine flexure is not considered, and only the displacement of the specimen is measured. Furthermore, the CLS test is a tensile test with a Carbon/Epoxy composite material that has a large stiffness in the warp direction, which leads to a high tensile force, that could cause slipping of the specimen on the grips, leading to a higher displacement measured by the machine.

Additionally, although actuator displacement works well for the ENF test, the 4ENF fixture is expected to have more "play" due to its larger complexity. Thus, to obtain precise ECM displacements, the displacement beneath each loading roller may need to be independently measured and averaged rather of using the test machine's actuator displacement. Otherwise, the fixture's compliance is factored into the test specimen's compliance calculation. These displacements can be measured using the DIC system underneath the rollers on the specimen itself.

The DIC measurement facilitates with measuring the displacement field of each specimen. Therefore, for each specimen it is necessary to choose the preferred points to retrieve the displacement. Special attention was needed for poor speckle patterns, where big speckles were taken out of the Area of Interest (AOI). This is necessary to not increase the projection error, which leads to inadequate displacement measurements. The AOI were chosen with the philosophy to reduce computational time but still capturing the necessary zone of measurements. For example, if cracks appear inside the AOI, since the crack would appear black to the DIC code, no speckle pattern is identified, hence no measurement would occur, and lead to a projection error increase. To prevent this, the crack plane from the crack propagation experimental tests, such as the 4ENF and CLS, was removed from the AOI. The same was applied to shadows that could appear within the face of the specimens.

3.4.1.1 DIC postprocessing of the TAST tests

A successful TAST will break in the middle of the specimen. For this reason, an AOI in the top or bottom arm can be used to measure the displacement. Since the top arm displacement considers more of the specimens' displacement, including the failure zone, this local measurement of the displacement will be used for all TASTs. The last value of the displacement when brittle failure occurs creates a jump in displacement on the top arm. This last data point is not meaningful, since the force is null, and so in the following graphs of the TASTs it is either removed or the displacement is changed to the last value before failure.

In Figure 32 it shows the different methods used to retrieve data from DIC. The two points, P0 and P1, are used to save the displacement of the top and bot arm, respectively. Then the rectangle R0 captures the average strain within its area, to be employed with the average stress calculated from the force measurement, $\sigma = P/Bl$ where l is the length of the crack zone and B is the thickness of the specimen. This stress vs strain data is used to confirm the shear modulus of the material. Finally, the line L0 recovers data from two hundred points along the line, namely the strain in transverse (opening mode) and shear, to obtain the strain along the crack zone and confirm the mainly shear effect in the TAST.

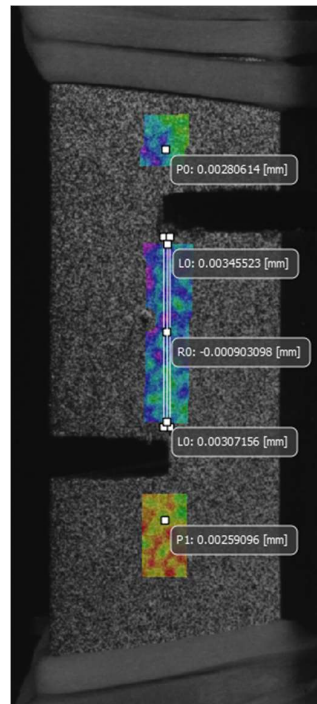


Figure 32 – DIC AOI of TAST n°3 in warp direction with the essential data.

3.4.1.2 DIC postprocessing of the 4ENF tests

From the analytical analysis and the literature (Kageyama, Kimpara et al. 1999, Martin and Davidson 1999, Schuecker and Davidson 2000, de Moura and de Morais 2008), the 4ENF displacement can be obtained through an average of the displacements of the loading rollers, as in Eq. (3.21):

$$\delta = \frac{w_L + w_R}{2} \quad (3.21)$$

where w_L and w_R are the displacement of the left and right loading pin, respectively. These displacements are not possible to recover from the loading pins themselves because they do not have the speckle pattern, and so the DIC is not capable of collecting data there. Hence, the data was retrieved right below the loading pins in the specimen, with the points P0 and P3 seen in Figure 33.

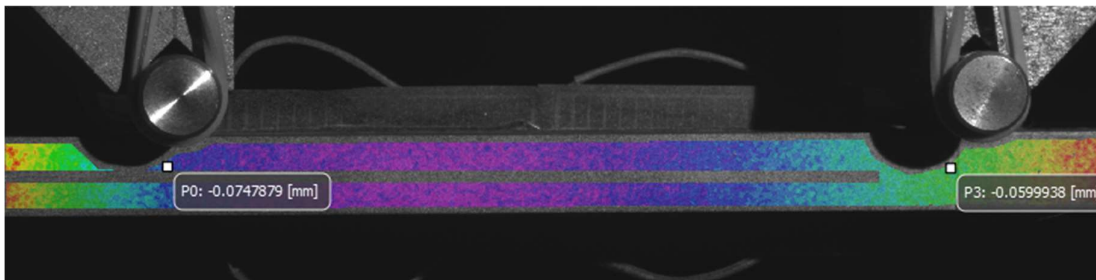
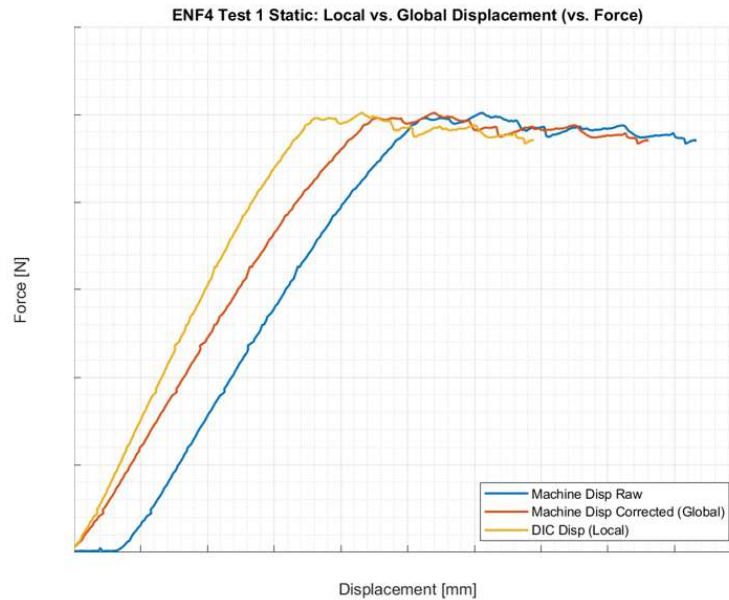


Figure 33 – DIC AOI of 4ENF test n°1 with the displacement points P0 and P3.

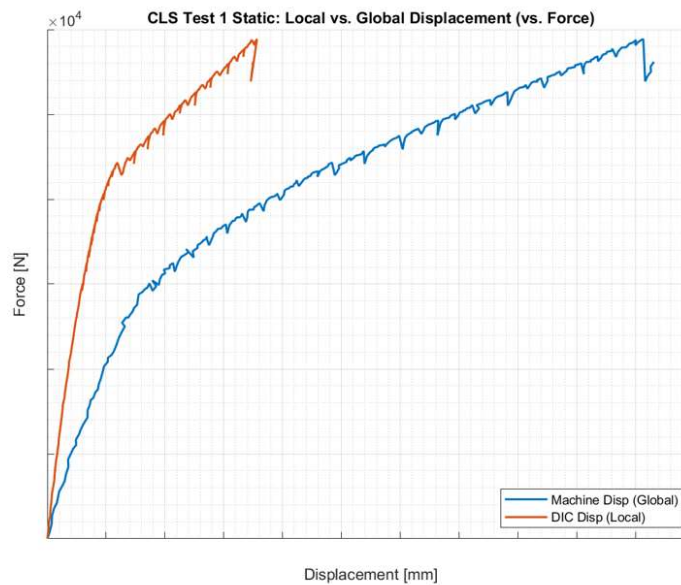
The data from this DIC analysis is compiled in a MATLAB code. Graph 4 shows three data lines. The first being the machine raw data, where it exists an initial phase where the rollers have a gap until they start inflicting load. The second is simply the machine data with the removed gap displacement. And the final data line is the displacement using the DIC data and Eq. (3.21). The machine flexure as a significant effect in the compliance measured, hence, from this point forward, only DIC displacement data is used for the ECM.



Graph 4 – 4ENF test n°1 with local (DIC with Eq. (3.21)) and global (machine) displacement.

3.4.1.3 DIC postprocessing of the CLS tests

Only one CLS test was performed, and the same conclusion is attained, as seen in Graph 5. During the test, it was observed that, due to high tensile loads, slipping of the specimen occurred at loads higher than 75% of the maximum load. This led to a misleading displacement from this load onward. Therefore, when using the ECM, the data after the slipping occurred is dismissed when achieving the R-Curve. The displacement from the DIC analysis was taken at the point P0, as seen in Figure 34, which take into consideration the displacement of the complete specimen.



Graph 5 – CLS test n°1 with local (DIC) and global (machine) displacement.

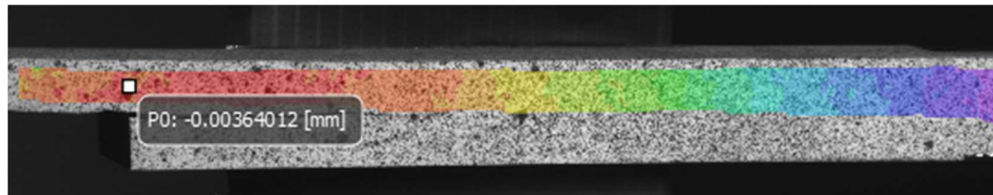


Figure 34 – DIC AOI of CLS test n°1 with the displacement point P0.

3.4.2 DIC projection errors

When conducting a correlation in Vic-3D, the Projection error is one of the numbers provided for each image. With an adequate test setup, projection error should be low – on the order of the calibration score, or in the 0.02-0.05 range. Slightly larger errors do not indicate a problem, but errors of 0.1 or more could indicate a problem (Correlated-Solutions 2016). These errors can come in many ways, for example a bad speckle pattern, poor calibration, or even heat waves rising from the light source.

In Table 7, the projection errors obtained in each test are reported. The first tests (TAST Warp) and the first 4ENF short specimen have errors greater than 0.1, which seems to be correlated to a poor speckle pattern. Although displacement and strain values can be used, the results of these tests cannot be guaranteed.

Table 7 – Projection errors from the DIC analysis

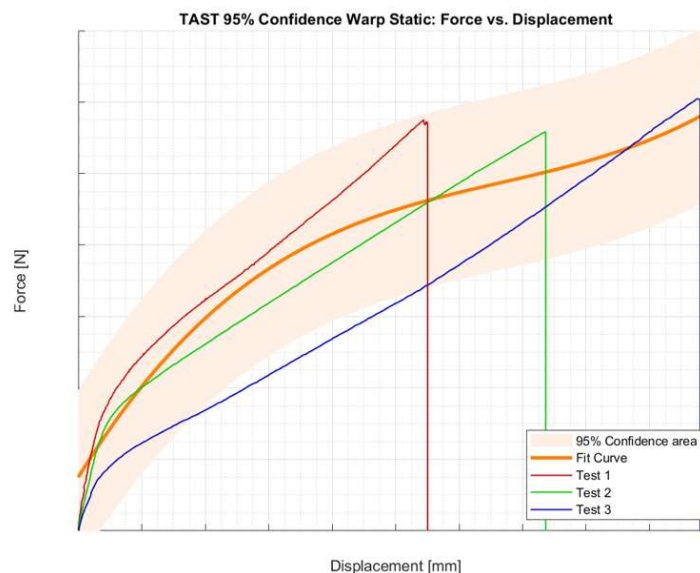
TAST Warp	TAST Weft	Short 4ENF	Long 4ENF	CLS
0.289 0.102 0.164	0.019 0.020 0.016	0.103 0.030	0.013 0.051 0.064	0.042

3.5 Static Results

In this section the results of the different experimental tests are presented, alongside a few remarks that were registered throughout the experiments. The individual tests are shown simultaneously, and with a fit curve (polynomial adjusted) and a 95% confidence region. This region is obtained through a statistical analysis an area where there is a 95% confidence region around the fit curve that the results are possible to develop. Singular results such as the strain along the crack path of a TAST will not have the 95% confidence region, since only one test is considered. For confidentiality reasons, all values shown will be normalized. The real loads and strengths will not be displayed.

3.5.1 TAST Warp Direction

The introductory result is the Load vs Displacement of all three tests completed, Graph 6. The failure displacement greatly changed from the 3 tests (can be a consequence from the poor DIC projection error), but the maximum force is an average of a normalised value of 1 N, with the length of the crack zone and the width of the specimen being equal to 8 and 25 mm, respectively, the interlaminar shear strength in warp direction can be calculated with Eq. (3.1), arriving at the normalized value of 1 MPa. The initial stiffness and subsequent change in slope do not have an identified effect. The potential causes are a wave effect of the 3D woven fibers; or focus of stress on the indents of the specimen, causing a change from a pure tensile effect throughout the entire specimen to a localized shear effect; or global shear damage that could occur during the test and decreases the stiffness of the entire specimen. No conclusion from these results is reached due to the high projection errors.

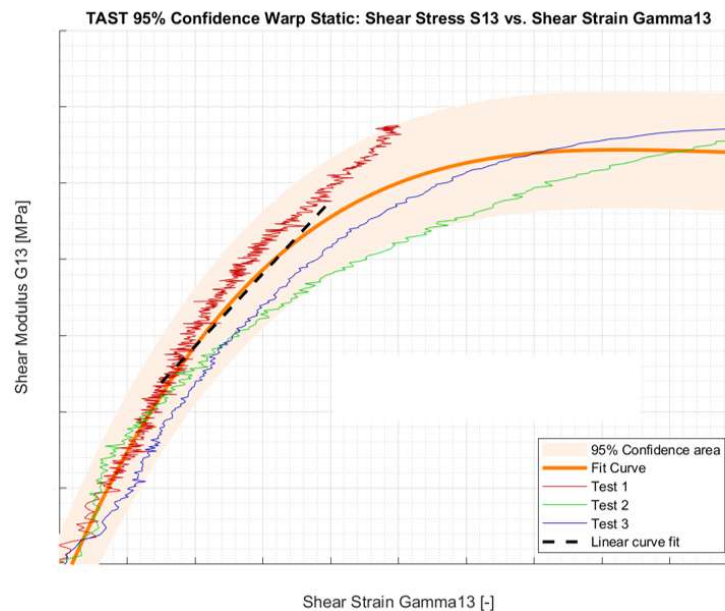


Graph 6 – TAST warp direction tests with 95% confidence region: Load vs Displacement.

The next result obtained from the TAST is the Stress vs Strain in the shear direction, where it is possible to reach the shear modulus to confirm the material data given. Graph 7 shows the slope of each individual test, while Graph 8 shows the slope of the fit curve from all three tests. The shear modulus was taken from the linear part of the Shear Stress vs Shear Strain curve, starting from 0.001 Shear Strain, since the initial curve could be affected by the compliance difference seen in the Load vs Displacement curve, Graph 6. This agrees with the standards (ASTM D3518) to attain the shear modulus, which also dictates that 0.004 strain in the linear curve is required to obtain the shear modulus, then the shear strain values for the linear fit curves are [0.001; 0.005]. The strain obtained through DIC is in the Lagrange form, and to obtain the shear modulus, it is necessary to change to pure shear strain γ by multiplying by two.



Graph 7 – TAST warp direction tests with individual linear slope curves: Shear Stress vs Strain.

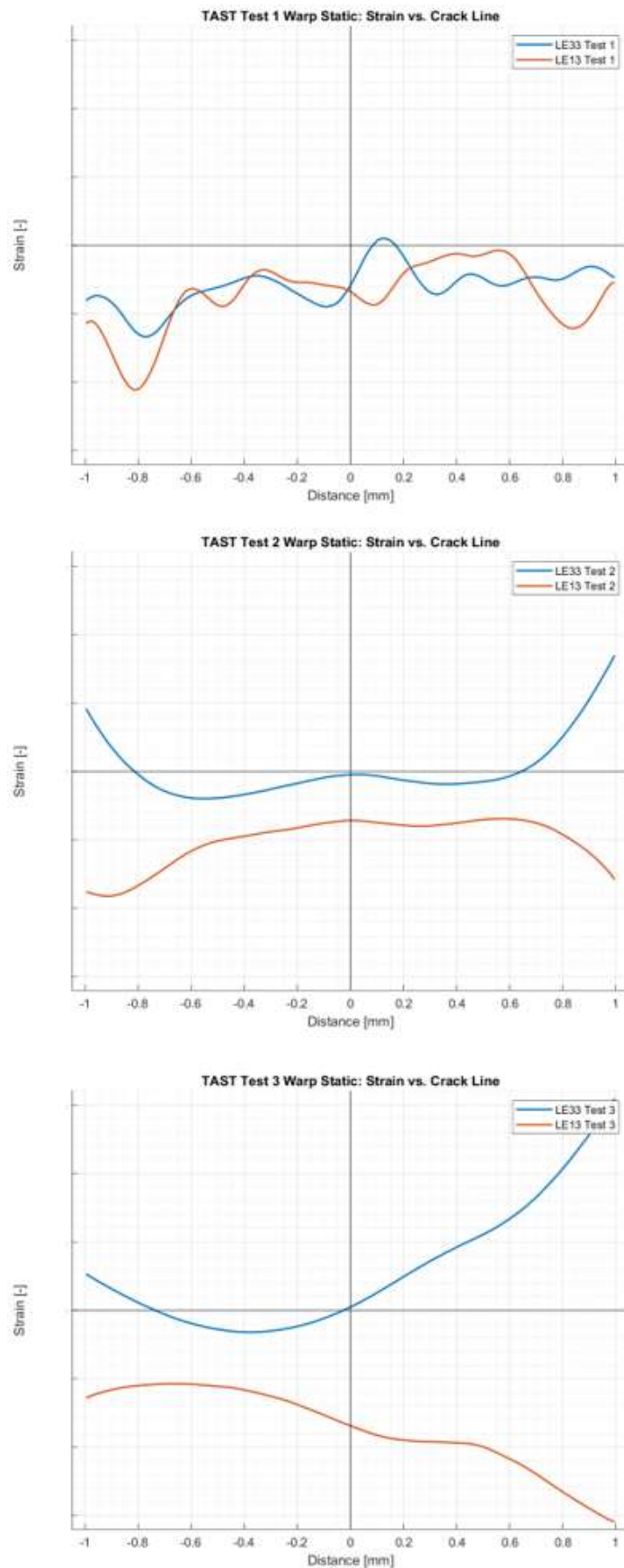


Graph 8 – TAST warp direction tests with 95% confidence region: Shear Stress vs Strain.

The shear modulus (G_{13}) obtained has an error of 87.7% compared to the expected value. Since the projection errors of these three tests were above 0.1, reported in Table 7, these findings are not guaranteed to be correct.

The last results to be reached is the shear and transverse strain along the crack line. Graph 9 displays the three tests' results before failure, and especially in the second test (with the lower projection error) is that the shear strain has the main influence, and the transverse strain is negligible along the crack line, concluding that the TAST is in fact a pure shear test. The distance is normalised to the centre of the crack line.

A microscopic analysis was done to the TAST specimens to identify the failure mode, which was found to be fiber/matrix interface debonding. Due to confidentiality, the fracture plane cannot be shown, but this type of failure mode was expected for a static test, as explained by Liu et al. (Liu, Nie et al. 2018) and in Section 2.3.2.



Graph 9 – TAST warp direction tests 1, 2 and 3: Shear and Transverse Strain along the crack.

3.5.2 TAST Weft Direction

The weft direction TAST Load vs Displacement result is displayed in Graph 10.



Graph 10 – TAST weft direction tests with 95% confidence region: Load vs Displacement.

The difference in force at failure seen in second test can be explained with the higher roughness of the crack plane in this test, as seen in Figure 35, comparably to the other weft tests. This higher roughness is expected in the weft direction since the fibers in this direction are not as straight as the warp fibers. This roughness can produce stress concentrations, leading to premature failure. From these results using Eq. (3.2) the normalised interlaminar shear strength in the weft direction is 60%.

The stiffness in Graph 10 appears to change steadily during the test, which could be justified through a diffuse damage behaviour of the matrix, because the matrix has a greater impact on stress distribution in the weft direction, due to lower fiber percentage in the direction of the stress, than in the warp direction.

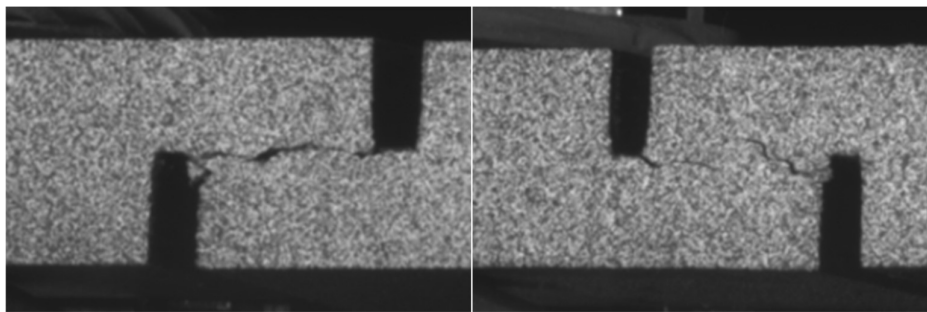
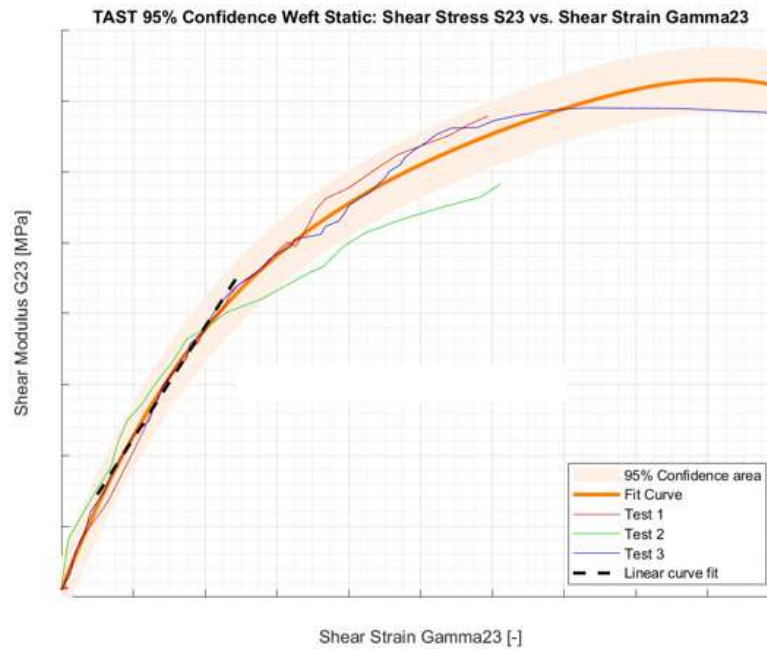


Figure 35 – TAST weft crack separation planes of test 1 (left) and test 2 (right).

The next result obtained from the TAST is the Stress vs Strain in the shear direction, where it is possible to reach the shear modulus to confirm the material data given. Graph 11 shows the slope of the fit curve from all three tests which all attained a similar curve.

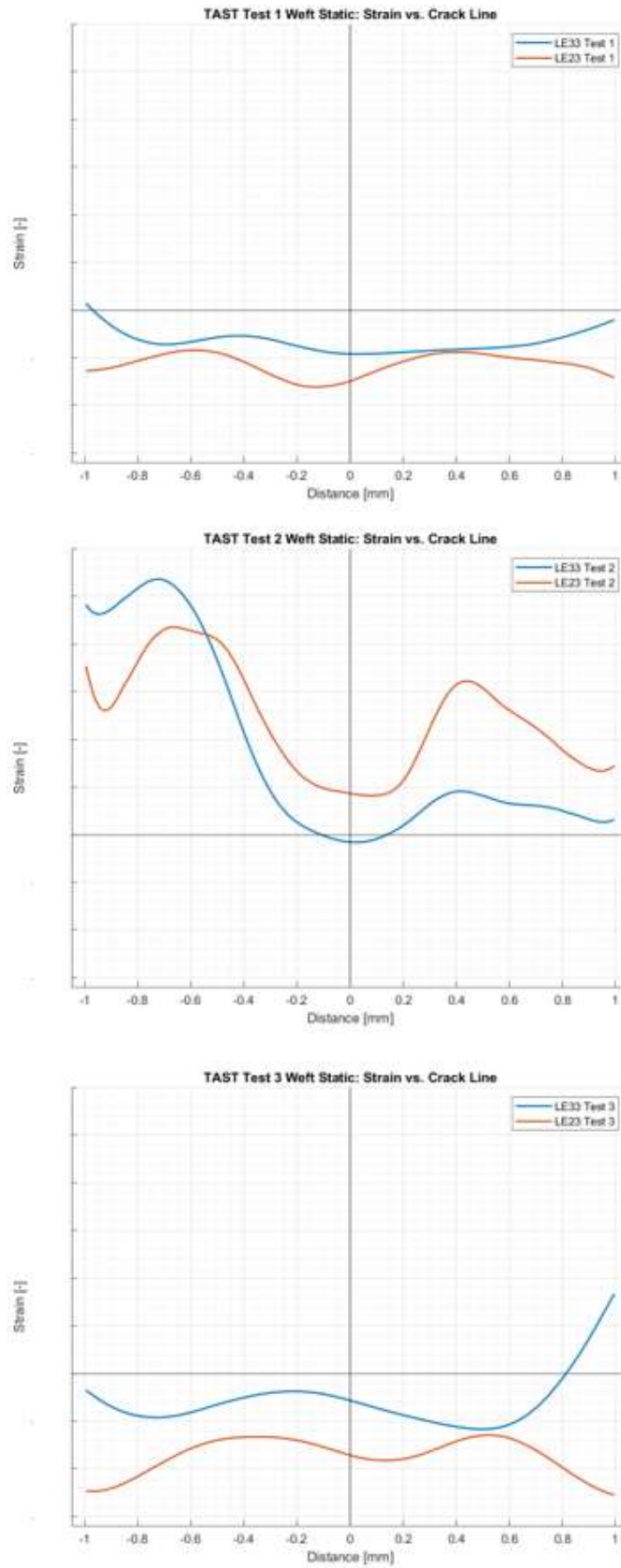


Graph 11 – TAST weft direction tests with 95% confidence region: Shear Stress vs Strain.

In the weft direction TASTs, the projection error is within acceptable values, which leads to correct measurements of the displacement in Graph 10 since all tests appear to fail at similar displacement, as well as correct strain measurements. This can be established because the shear modulus in weft direction given for the material properties (G23) is close to the one obtained in the experimental test, Graph 11, with a small error of 2.1%.

Lastly, the shear and transverse strain along the crack line. Graph 12 displays the three tests' results before failure. The same conclusion from the warp tests is achieved, where the shear effect has more of an influence in the crack line. Miscellaneous strain values on the test 2 is due to the roughness effect seen in Figure 35 on the right that caused a change in strain before complete failure.

The same fracture mode analysis can be done for the weft specimens, where debonding of the fiber/matrix interface was observed. Therefore, the same failure mode as the warp tests.

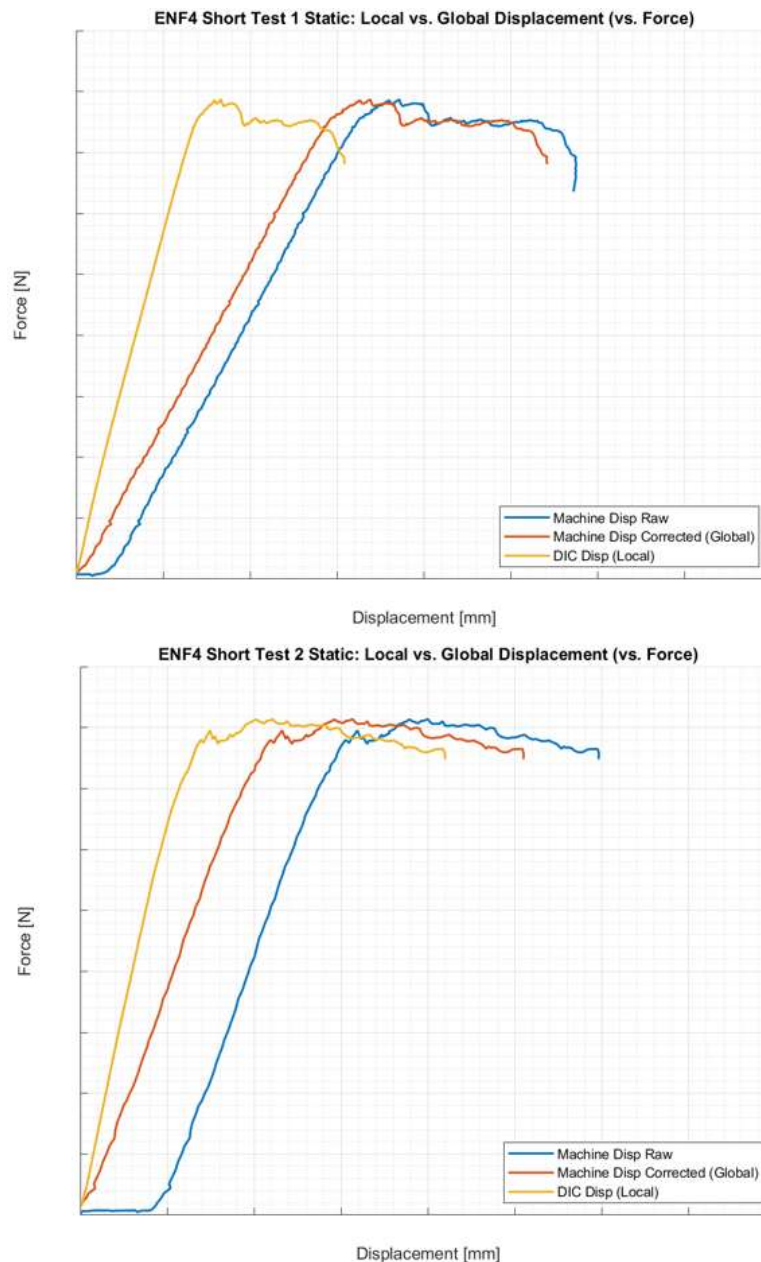


Graph 12 – TAST weft direction tests 1, 2 and 3: Shear and Transverse Strain along the crack line.

3.5.3 Short 4ENF Specimen

Although these specimens were mainly used to mature the 4ENF procedure, they were also used for comparison of the friction effect of the 4ENF depending on the size of the specimen.

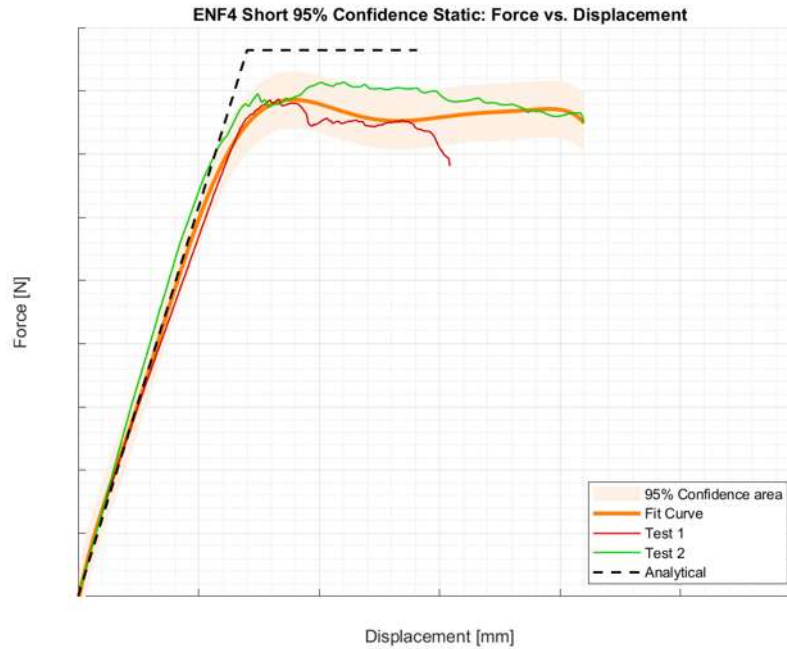
With the short samples, since no crack gauge was used to obtain the crack propagation during the test, only Load vs Displacement curve can be attained. From this point forward, the results will also show the analytical solution predicted with the sizes of the specimens and the value of DFT calculated *a posteriori* from the Long 4ENF specimen, since it is expected to have a lower friction effect. Furthermore, when the experimental set up was done, the measurement of the real crack length was different than the designed one, changing from 35 mm to 38 mm.



Graph 13 – Short 4ENF tests with local (DIC with Eq. (3.21)) and global (machine) displacement.

In Graph 13 the machine raw data, machine zeroed data, and DIC data are presented, for the first test (above) and the second test (under).

The specimens behaved as expected, this is, when crack started to propagate a plateau in force was expected. It was noticed that the flexure effect of the machine was different in different test. But with the DIC displacement values it is possible to obtain a more consistent outcome. GRAPH 13 shows the results of both tests and the 95% confidence region and the analytical curve. The difference in force between the experimental and analytical results is due to the DFT value used being from the Long 4ENF specimen results in Section 3.5.4, and also the fact that LEFM is employed to determine the analytical solution, so, non-linear effects, for example diffuse damage or the friction effect, are not considered.



Graph 14 – Short 4ENF experimental results with 95% confidence area: Load vs Displacement.

A plateau during crack propagation was expected, and the initial slope should be the same as the analytical one since damage and other non-linear effects would not be developed yet. As a result, the experiment was a success.

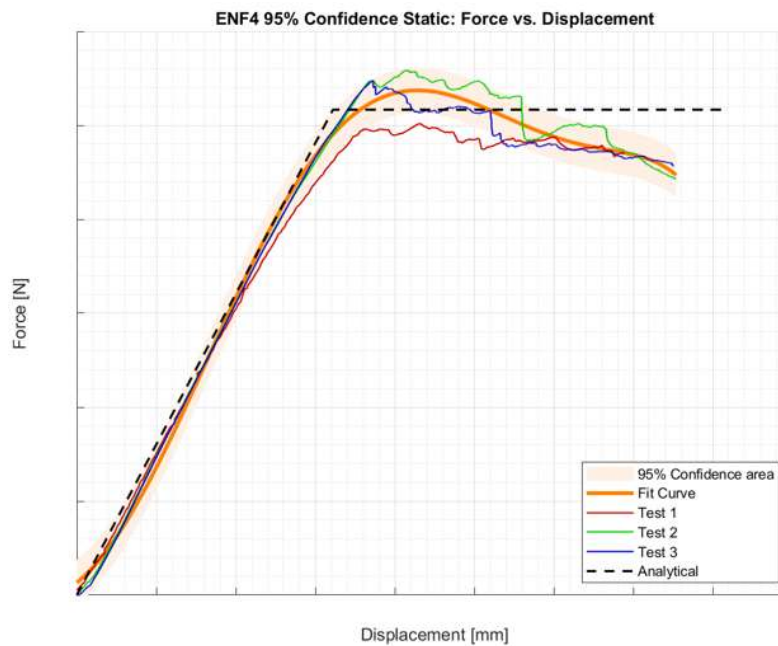
3.5.4 Long 4ENF Specimen

A crack gauge to measure the crack length during the experiment was used in this test. This measurement can be used to get the Crack Length vs Displacement curve, the Compliance vs Crack Length curve, which is utilised to obtain the $\partial C / \partial a$, and finally, the R-Curve.

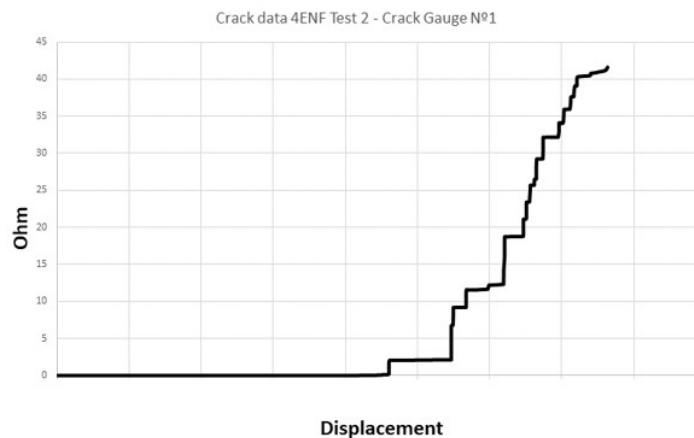
The Load vs Displacement curves are displayed in Graph 15 along with the analytical solution, using the attained value of DFT calculated *a posteriori*. Knowing that the position of the loading rollers influences the initial crack dimension, special attention to the set up was done in order to try and minimise the difference between designed and real crack length of the experimental test, which was done successfully. Then the crack data is obtained from the crack gauge. The raw data shows the jumps in ohm when the crack propagates through the gauge strings Graph 16. Knowing the distance between the strings (2 mm), the distance between the two crack gauges in sequence, and when the crack is located during propagation it is possible to attain the points of Crack length vs Displacement, Graph 17. From analytical

and numerical it is known that this curve is approximately linear, which agrees with the experimental results.

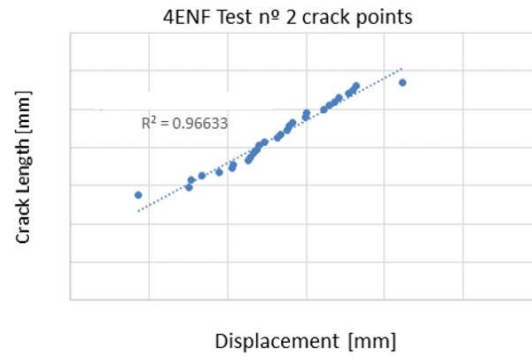
This leads to Graph 18 which encapsulates the three tests' results and the analytical solution for the linear Crack length vs Displacement. Afterwards the Compliance vs Crack length curve, Graph 19, which its derivative is used to attain the R-Curve as the ECM dictates. The R-Curve is shown in Graph 20. The obtained value (not shown for confidentiality reasons) will be utilised in the analytical solution graphs along with the numerical models as the DFT for pure Mode II.



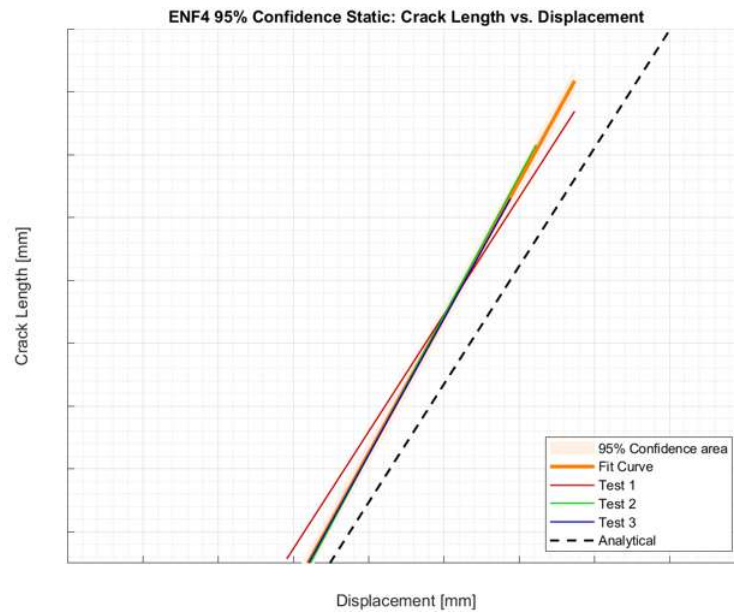
Graph 15 – Long 4ENF tests and analytical solution: Load vs Displacement.



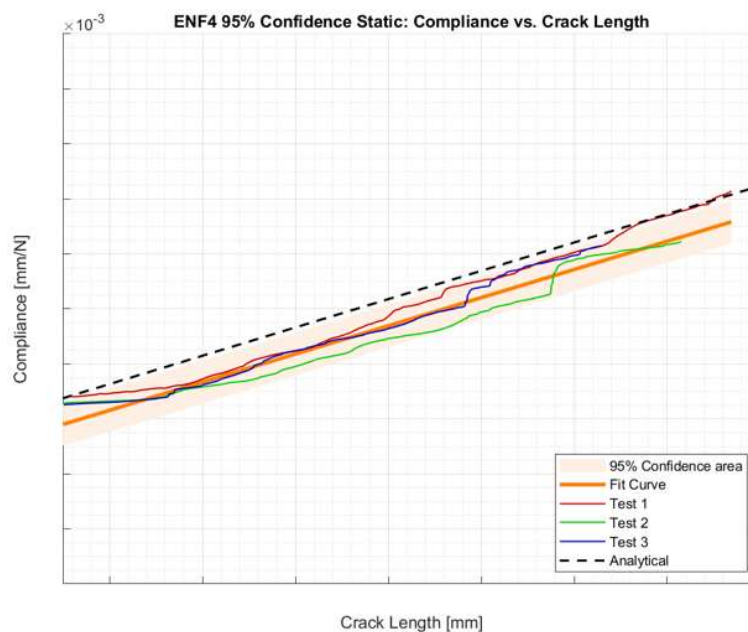
Graph 16 – Long 4ENF test n°2 crack data: Ohm vs Displacement from Crack Gauge n°1.



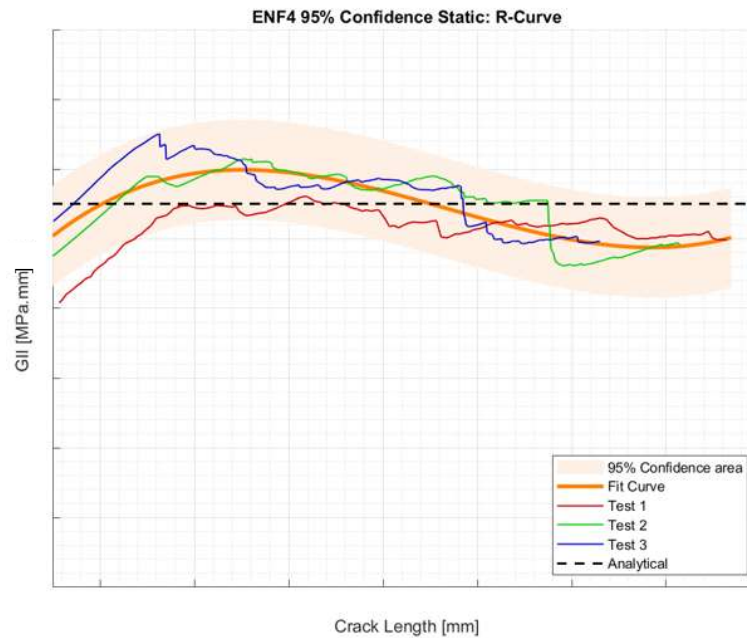
Graph 17 – Long 4ENF test n°2 Crack vs Displacement points.



Graph 18 – Long 4ENF tests and analytical solution: Crack Length vs Displacement.



Graph 19 – Long 4ENF tests and analytical solution: Compliance vs Crack Length.



Graph 20 – Long 4ENF tests and analytical solution: R–Curve.

Figure 36 and Figure 37 are the crack evolution from 76% to 100% of the total test duration. From these figures, it's clear that the crack doesn't propagate much further, and out of centre plane cracks start to appear in the middle of the specimen, due to the bending stresses. The use of crack gauges helps with the identification of the crack length because its data shows that the crack stops to propagate at the moment of Figure 36. This means that the data afterwards is unusable to the determination of DFT using the ECM.

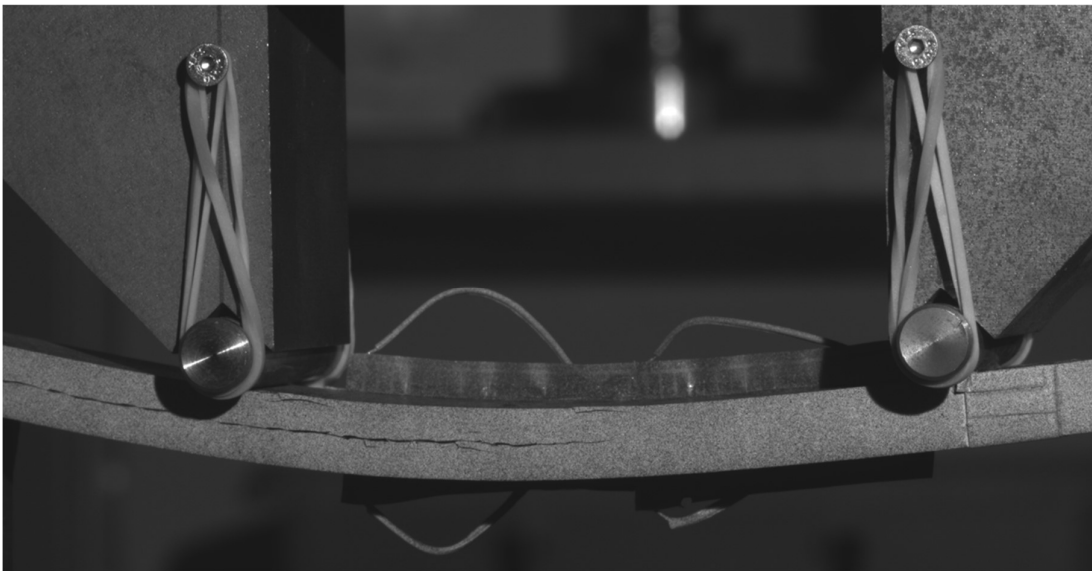


Figure 36 – Long 4ENF test DIC image 2 at 76% of the duration of the test (crack propagation stopped).



Figure 37 – Long 4ENF DIC image at 100% of the duration of the test (end of the test).

3.5.5 CLS

Due to lack of time, only one test was completed, hence no 95% confidence curve won't be done since there is not sufficient data.

Alike the 4ENF test, the ECM was employed, and from the measured data we obtain four graphs. Unfortunately, the fracture data from the crack gauges was not properly preserved since they were not properly set up, requiring an examination of the DIC images. By counting the number of pixels on the crack at one point during the test, the crack length could be estimated. This visual analysis is a simplification due to the difficulty finding the crack tip. Knowing that the Crack length vs Displacement curve is linear from analytical and numerical models, the crack data was estimated. Figure 38 shows examples of DIC images where the length of the crack is highlighted that were used to estimate the crack data.

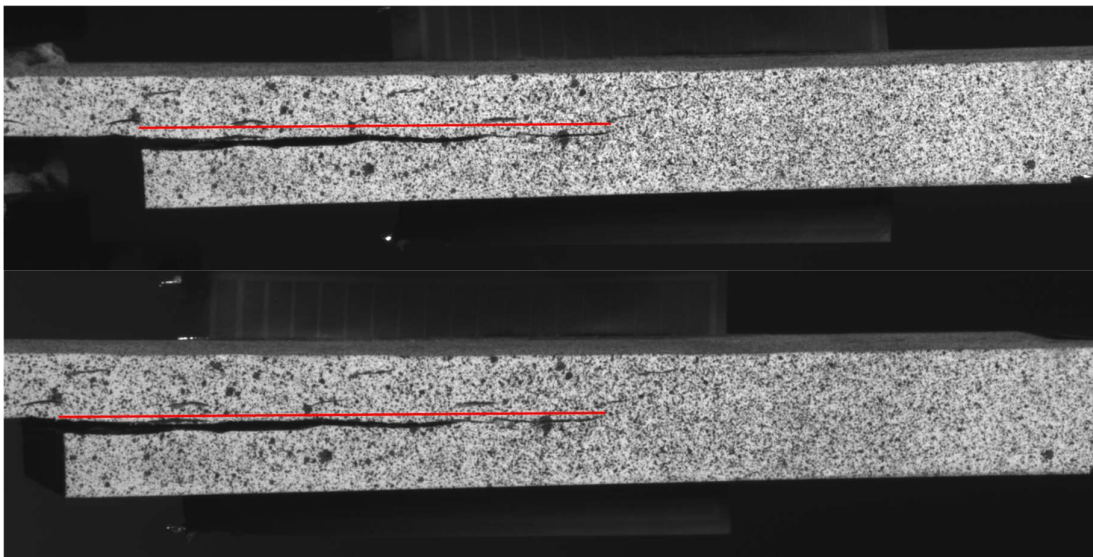
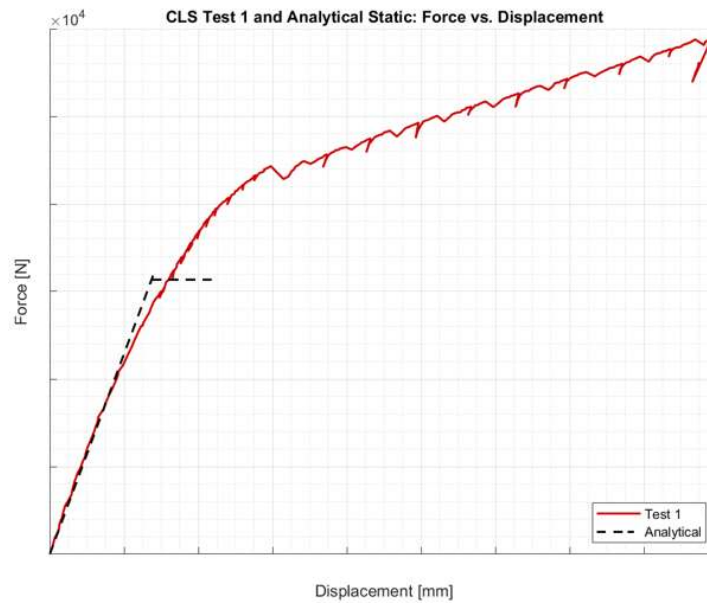
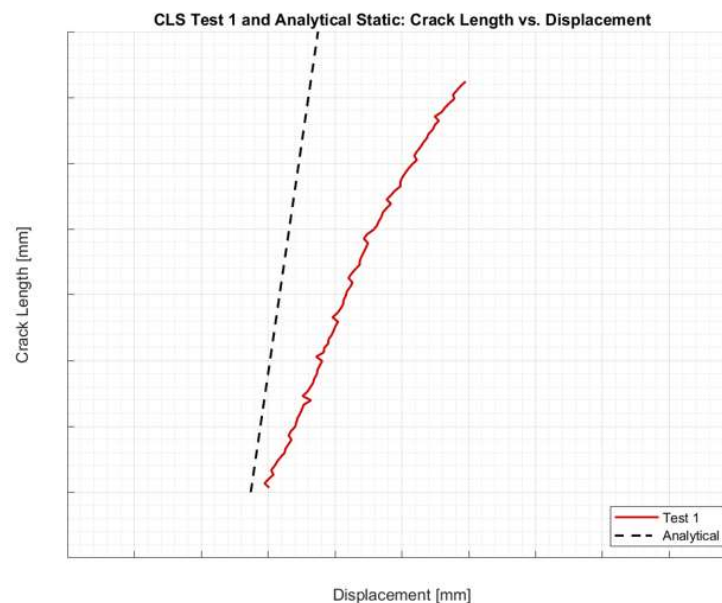


Figure 38 – DIC images taken during the CLS test experiment with highlighted crack length.

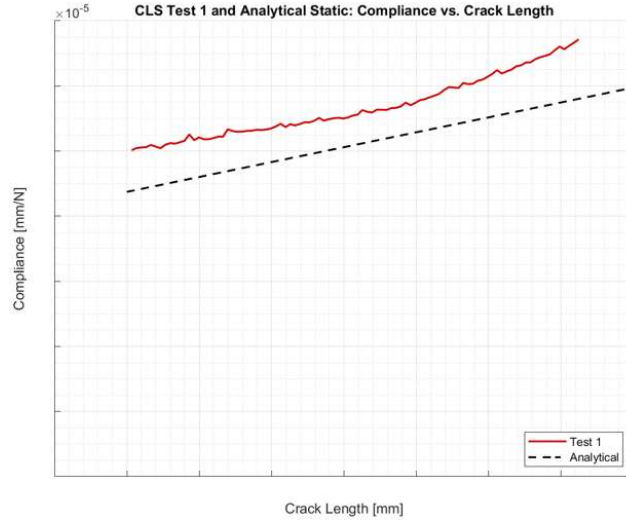
The next set of graphs, Graph 21 is the Load vs Displacement plot, Graph 22 is the Crack Length vs Displacement plot, Graph 23 is the Compliance vs Crack Length plot, finally, Graph 24 is the R-Curve plot, and these are the results obtained from the CLS test. As previously said, the data after 75% of the load is shown but it is not used in the ECM since slipping of the specimen occurred, leading to a difference in displacement and subsequently in compliance. The CLS specimen's behaviour is divided into three main parts. The first part involves elastic deformation, where the specimen deforms under external forces, acquiring elastic energy before reaching the critical energy threshold. The second part involves the sudden deviation of the curve due to the initiation of the pre-crack, causing structural changes and reduced resistance. The third part involves the crack reaching the upper end, splitting into two independent parts, and ultimately causing the total rupture of the arm-loaded specimen. This behaviour is the same as Tran (Tran 2011) identified.



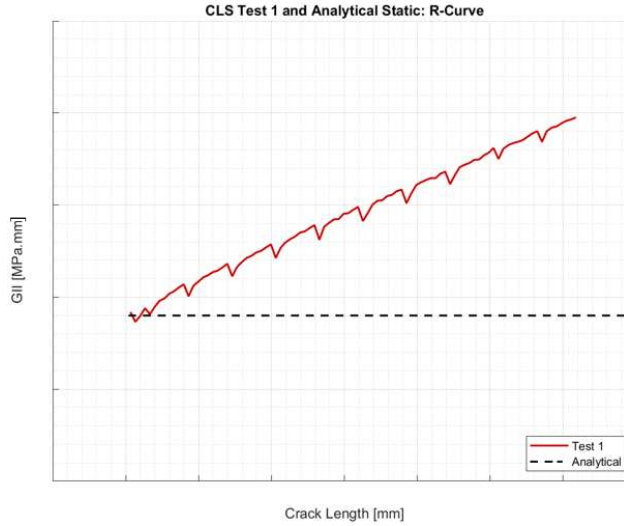
Graph 21 – CLS test 1 and analytical solution: Load vs Displacement.



Graph 22 – CLS test 1 and analytical solution: Crack Length vs Displacement.



Graph 23 – CLS test 1 and analytical solution: Compliance vs Crack Length.



Graph 24 – CLS test 1 and analytical solution: R-Curve.

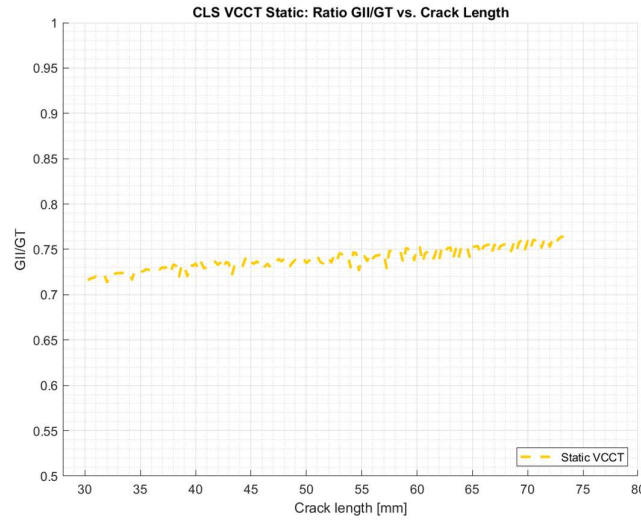
Graph 24 shows that the initial DFT quantity for the CLS specimen is more than five times smaller than the one obtained in the 4ENF test. Furthermore, the R-Curve had the tendency to increase during propagation. Giving that in Figure 38 it is possible to see an opening mode behaviour (Mode I), which aimed to do an analysis on the ratio between Mode I and Mode II. This mix-mode behaviour was expected, since no part inhibiting the opening of the arms was used during the test. Using the VCCT model described in Section 5, it is possible to identify the mix-mode ratio. This ratio is expressed in Eq. (3.22). This is calculated using the displacements of the nodes in Mode I (δ_I) and in Mode II (δ_{II}). The variable $\beta = \delta_{II}/\delta_I$, is used to reach the ratio G_{II}/G_T using Eq. (3.23), equation reached in Annex D in Eq. (D.9).

$$\frac{G_{II}}{G_T} = \frac{G_{II}}{(G_I + G_{II})} \quad (3.22)$$

$$\frac{G_{II}}{G_T} = \frac{\beta^2}{1 + \beta^2} \quad (3.23)$$

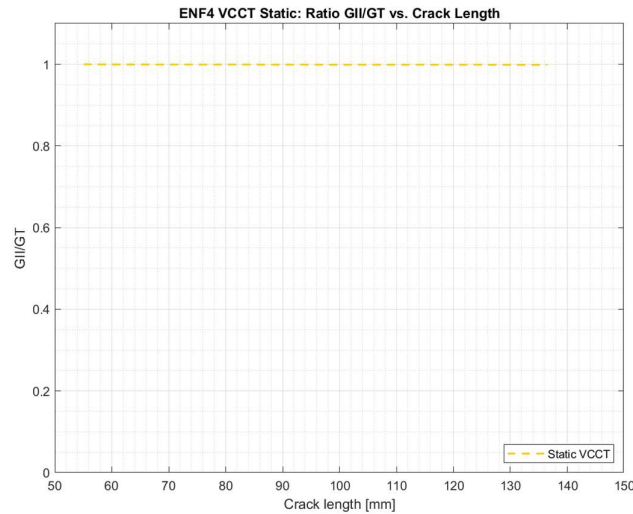
When pure Mode I is present, the ratio and β are equal to 0. Whilst in pure Mode II, the ratio is equal to 1, while β is equal to infinite.

Graph 25 shows the evolution of the ratio during crack propagation for the CLS test, and the initial ratio value is 0.7143 (or $\beta^2 = 2.5$), meaning it is a mix-mode test and not pure Mode II. Furthermore, there is an increase in the ratio, which leads to an increase in the DFT during propagation, since $G_{IC} < G_{IIC}$. This corresponds well with the experimental results seen in Graph 24. This mix-mode DFT value will be useful to determine the B-K criterion parameter.



Graph 25 – CLS Numerical VCCT: G_{II}/G_T Ratio vs Crack Length.

As a confirmation that the 4ENF test is a pure Mode II test, Graph 26 shows the mix mode ratio at a constant value of 1.



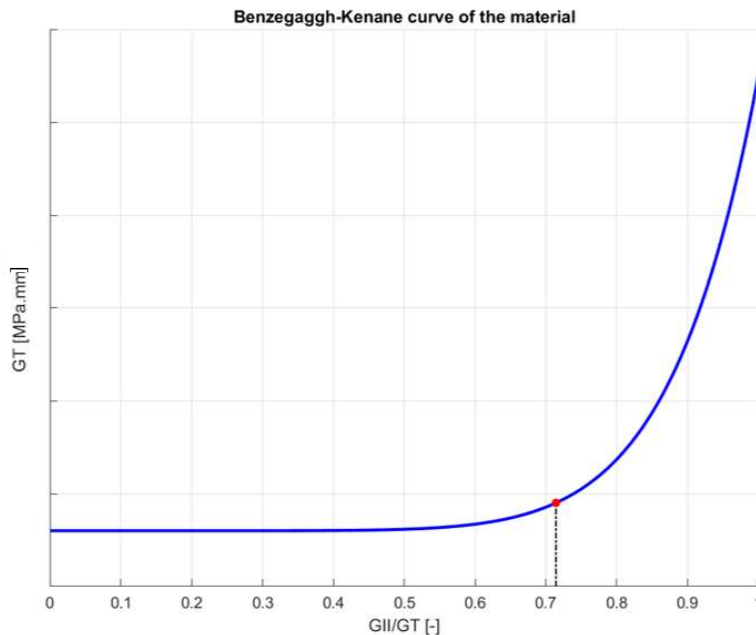
Graph 26 – Long 4ENF Numerical VCCT: G_{II}/G_T Ratio vs Crack Length

3.6 Cohesive Material Proprieties for Numerical Models

Safran provided the elastic material properties of the 3D woven angle interlock composite. It was possible to determine some cohesive properties through the experiments performed in this test campaign. Further variables that could not be obtained experimentally were assumed using examples and considerations from the literature.

First, the main objective of the test campaign was the R-curve. However, the CZM only utilizes three values for DFT, one for each mode of delamination. One assumption commonly used is that the Mode II and Mode III can assume the same value. Since the 4ENF test is a pure Mode II test, the $G_T = G_{IIc}$ was obtained at a value of $1 \text{ MPa} \cdot \text{mm}$. Then, with a mix mode ratio of 0.7143, the $G_T = G_{I+II}$ has the value of 16.4%. No DCB test was performed, but from a typical value for a Carbon/Epoxy composite a DFT for Mode I can be assumed, with the consideration that must be lower than the value obtained in the CLS test. Therefore, the value for G_I was assumed at 10.9%.

With these 3 points, it is possible to find the B-K parameter, which was found to be 8.3. This is a large number for this parameter, which, as seen in Graph 27, this material abruptly increases the energy it is capable of releasing when it moves closer to a Mode II delamination.



Graph 27 – Benzegagh-Kenane curve of the material studied, obtained from experimental results.

The next values to be taken from the experimental results is the interlaminar shear strength, from the TASTs. In warp direction, this value was 1 MPa, while in weft direction was 60%.

On the other hand, the opening mode (Mode I) strength, or in other words, interlaminar peel strength is not possible to obtain from a specific test and is usually inferred. From the literature, changing this value in the numerical models gives negligible difference in the results (Silva, de Moura and Morais 2006).

The value will then be assumed at 75%, smaller than the interlaminar shear strength, since decreasing the interlaminar strength values in the cohesive elements helps the convergence of the model because the length of the cohesive zone and the number of elements in the cohesive zone increase. Therefore, the representation of the softening response of the

fracture process ahead of the crack tip is more accurate with a lower interface strength without any difference in the final results (Alfano 2006).

The final material property necessary is the stiffness of the cohesive elements. As explained in Section 2.4.1.2, this value must be high enough to prevent interpenetration of the element faces, but not too high otherwise it causes numerical issues. Camanho et al. and Turon et al. (Camanho, Davila and de Moura 2003, Turon, Dávila et al. 2007) propose that the value of 10^6 is an appropriate choice for K . Another way to calculate the stiffness is using Eq. (3.24) (Turon, Dávila et al. 2007), whose values are in the same order of magnitude can be obtained, so 10^6 will be the stiffness to be used in the ABAQUS cohesive material.

$$K = \frac{\alpha E'}{t} \quad (3.24)$$

where $t=0.01$ mm is the thickness of the cohesive elements, α is a multiplication factor normally being equal to 50, and E' the stiffness of the composite material in the direction of interest. For Mode I, E' is E_3 , while for Mode II, E' is $2 \cdot G_{13}$. The stiffness for every mode is presumed to be the same value for simplicity. The complete cohesive material properties are reported in Table 8, missing only the viscosity which is attained through a convergence method.

Table 8 – Cohesive Material Properties normalized used in CZM

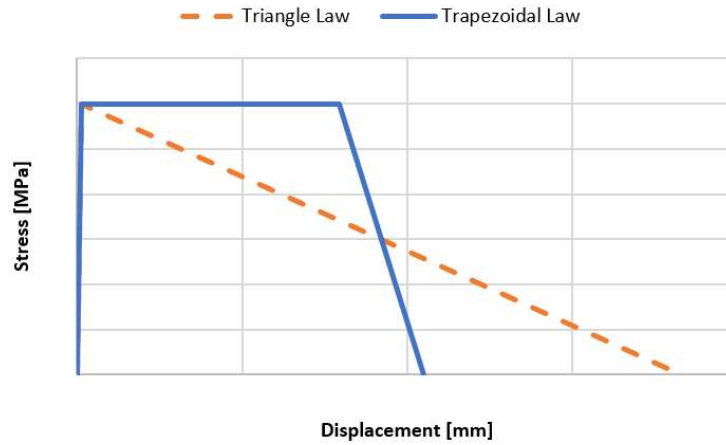
G_{Ic}	$G_{IIc}=G_{IIIc}$	τ_{33}	τ_{13}	τ_{23}	$K_I=K_{II}=K_{III}$	η
[MPa · mm]	[MPa · mm]	[MPa]	[MPa]	[MPa]	$\left[\frac{\text{MPa}}{\text{mm}}\right]$	[-]
10.9%	1	75%	1	60%	1000000	8.3

4 User Material

In the beginning of this thesis, the UMAT was to impose the strain rate effect. However, with the large value for the G_{IIc} that leads to a high FPZ, and the high variation in DFT when the mixed mode ratio, β , changes during propagation, the UMAT could also try to reduce these difficulties. The increase in FPZ can lead to misleading results since the stress concentration on the crack tip could be misrepresented. This situation is created due to the displacement at failure of the cohesive elements' nodes being bigger because of the increase in G_{IIc} . Since the model has insufficient displacement on the nodes to break the cohesive elements, the stress is spread across a larger area.

And how can it be possible to reduce the displacement at failure? By changing the cohesive law, from a triangle law to a trapezoidal law. Using the same interlaminar strength, the same stiffness, and the same DFT, the displacement at failure will reduce, since the trapeze will better enclose the DFT, in other words the area, than a triangle, as seen in Graph 28, which exhibits an example curve for the two cohesive laws in analysis.

Example of representation of the new cohesive law



Graph 28 – Trapezoidal and Triangle Laws with the same DFT, in other words, the area below the curve.

4.1 UMAT Formulation

To define a trapezoidal cohesive law, besides the variables previously mentioned, one parameter needs to be defined. This parameter defines the relation between the displacement at max stress of the initial slope, δ_0 , and the max displacement of the plateau, δ_c , as Eq. (4.1) expresses:

$$\delta_0 = p\delta_c \quad (4.1)$$

This parameter is not a material property, and its value is completely arbitrary, with the conditions $\delta_c < \delta_f$ and making sure that the area does not exceed the max DFT value.

To overcome the decision of this parameter and knowing that the large FPZ issue doesn't occur at lower values of DFT a new cohesive law was created.

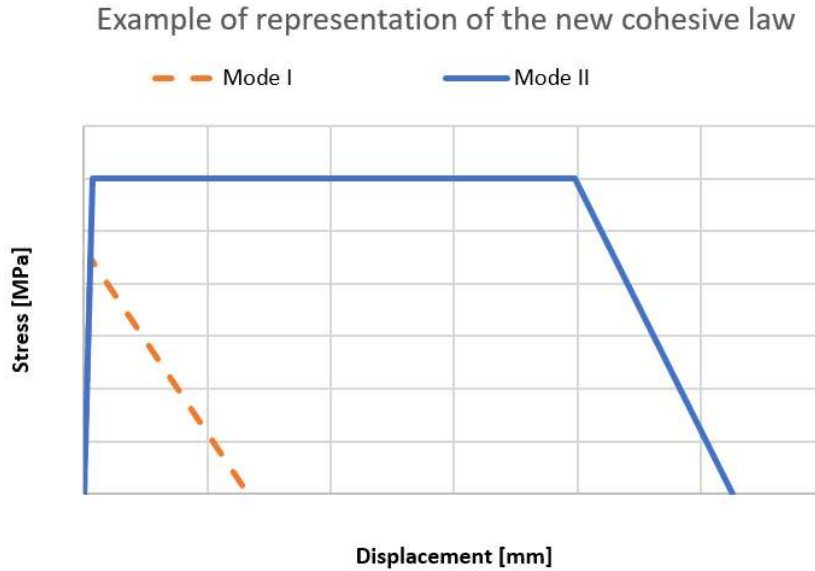
With the low DFT in Mode I, the triangle law doesn't have a problem representing the FPZ, therefore only when the behaviour is closer to Mode II it is necessary a trapezoidal law. So, the size of the plateau is determined by the mixed mode ratio, β , where the increase in this ratio, which increases the DFT, also increases the δ_c . This means that in pure Mode I, the behaviour would be similar to a triangle law, and the mix-mode and pure Mode II behaviour would be represented with a trapeze.

On the normal trapezoidal law, the δ_f is determined using the DFT, so, in this new cohesive law, since the δ_c is already determined with this method, another consideration is necessary to define the δ_f .

This assumption is: the difference ($\delta_f^I - \delta_c^I$) in Mode I will be constant throughout the entire behaviour, in mixed mode and pure Mode II. Since $\delta_c^I = \delta_0^I$, δ_c^I doesn't utilise the area calculation, and so the final displacement can use this method, with Eq. (4.2).

$$\delta_f^I = 2G_{Ic} / \sigma_0^I \quad (4.2)$$

Graph 29 shows an illustration of this new cohesive law, described in the former paragraphs, using the cohesive material properties of the material in analysis (namely the interlaminar strength and DFT for both modes of delamination).



Graph 29 – Illustration of the new cohesive law for Mode I and II with the cohesive material properties.

In reality, even though the shape of the Mode I behaviour looks like a triangle, the law is still a trapezoidal shape, where the top plateau is null.

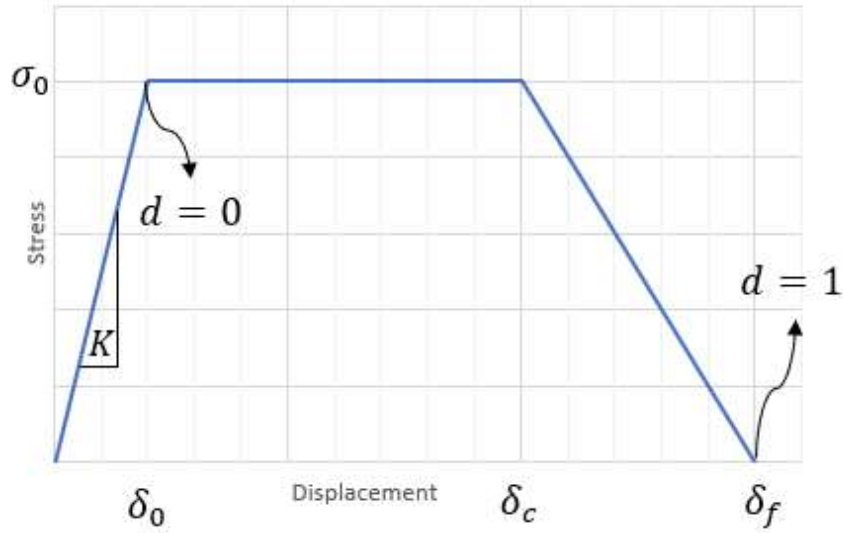
The formulation of the stress in this type of law is as Eq. (4.3) describes, where the displacement, δ , is the main variable to reach the stress.

$$\sigma = \begin{cases} K\delta & 0 \leq \delta \leq \delta_0 \\ \sigma_0 & \delta_0 \leq \delta \leq \delta_c \\ \frac{\sigma_0}{\delta_f - \delta_c}(\delta_f - \delta) & \delta_c \leq \delta \leq \delta_f \\ 0 & \delta \geq \delta_f \end{cases} \quad (4.3)$$

where σ is the stress to be calculated, σ_0 is the interlaminar strength, δ is the actuating displacement, and δ_0 , δ_c , δ_f are the displacement to be calculated that represent the trapeze, as seen in Graph 30.

To use the actuating displacement to reach the stress, it is used a damage parameter that evolves according to the displacement. The conditions are:

$$d: \begin{cases} d = 0 & \text{at } \delta \leq \delta_0 \\ d = 1 & \text{at } \delta \geq \delta_f \end{cases} \quad (4.4)$$



Graph 30 – Definition of parameters of the trapeze cohesive law.

This means that the damage parameter has two regions where it evolves and needs to be defined. The complete resolution is in 0.

Eq. (4.5) defines the damage parameter, first in the plateau, then in the declining ramp.

$$d = \begin{cases} 1 - \frac{\delta_0}{\delta} & \delta_0 \leq \delta \leq \delta_c \\ 1 - \frac{\delta_0}{\delta_c - \delta_f} \cdot \left(1 - \frac{\delta_f}{\delta}\right) & \delta_c \leq \delta \leq \delta_f \end{cases} \quad (4.5)$$

Now, it is required to define the various displacements of the law. The quadratic stress criterion is used to determine the δ_0 . While δ_c is obtained through the B-K Law, and δ_f is through the difference defined previously, $\delta_f = \delta_c + (\delta_f^I - \delta_c^I)$. These parameters are calculated with Eqs. (4.6) and (4.7), and the complete determination is in 0.

$$\delta_0 = \delta_0^I \delta_0^{II} \sqrt{\frac{1 + \beta^2}{\delta_0^{II^2} + (\beta \delta_0^I)^2}} \quad (4.6)$$

$$\delta_c = \frac{1}{K \delta_0} \left[G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^\eta \right] + \frac{\delta_0}{2} - \frac{G_{Ic}}{\sigma_0^I} + \frac{\sigma_0^I}{2K^I} \quad (4.7)$$

with Eqs. (4.8) being the auxiliary expressions:

$$\begin{aligned} \beta &= \frac{\delta^{II}}{\delta^I} \\ \delta &= \sqrt{\delta^{I^2} + \delta^{II^2}} \\ \delta^{II} &= \sqrt{\delta_{13}^2 + \delta_{23}^2} \end{aligned} \quad (4.8)$$

and the relations between the displacements, the stresses, the DFT and the stiffnesses (where $i = I, II$ for representing both modes, and if there are no indexes, it represents the mix mode behaviour) are:

$$\begin{aligned} \sigma_0^i &= K^i \delta_0^i \\ G_i &= \frac{\sigma_0^i}{2} (\delta_f^i + \delta_c^i - \delta_0^i) \\ \frac{G_{II}}{G_T} &= \frac{\beta^2 K^{II}}{\beta^2 K^{II} + K^I} \\ K &= (K^{II} - K^I) \frac{\beta^2}{\beta^2 + 1} + K^I \end{aligned} \quad (4.9)$$

Finally, it is essential to arrive at the mode specific displacements of the trapeze law, which are directly calculated from the input cohesive material properties, as Eqs. (4.10), (4.11), (4.12) demonstrate. Eqs. (4.13) and (4.14) were previously inferred, but for the sake of completeness, it is recorded below.

$$\delta_0^i = \frac{\sigma_0^i}{K^i} \quad (4.10)$$

$$\delta_c^I(\beta = 0) = \delta_0^I = \frac{\sigma_0^I}{K^I} \quad (4.11)$$

$$\delta_c^{II}(\beta = \infty) = \frac{G_{IIc}}{\sigma_0^{II}} - \frac{G_{Ic}}{\sigma_0^I} + \frac{\sigma_0^{II}}{2K^{II}} + \frac{\sigma_0^I}{2K^I} \quad (4.12)$$

$$\delta_f^I = \frac{2G_{Ic}}{\sigma_0^I} \quad (4.13)$$

$$\delta_f^{II} = \delta_c^{II} + (\delta_f^I - \delta_c^I) \quad (4.14)$$

where K stands for the stiffness of the cohesive law, G_c is the DFT and σ_0 is the interface strength, where i represents the index for both delamination modes in each parameter. These six variables derive from the cohesive material properties. Mode II encloses both itself and Mode III, as the last equation in Eqs. (4.8) displays. With Mode III, the B-K parameter, the viscosity, and the maximum damage (set at 0.9999), the UMAT has a total of twelve material properties.

Section 2.4.2 specifies that for the UMAT to converge with the static formulation, the Jacobian matrix needs to be developed. The development of this matrix for the trapeze law is reached in 0. Eq. (4.15) is the definition of the Jacobian matrix.

$$\frac{\partial \sigma}{\partial \varepsilon} = \frac{\partial}{\partial \delta^i} [(1 - d)K^i \delta^i] = (1 - d)K^i - \frac{\partial d}{\partial \delta^i} \sigma^i \quad (4.15)$$

The tensor σ can be simplified to an identity matrix, and so i is the position along the diagonal of the matrix, for opening mode, shear in Mode II and Mode III, respectively. As previously explained, the strain can be substituted with the displacement of the nodes of the cohesive elements. This leaves the parameter $\partial d / \partial \delta^i$ the only one left to calculate. Since the damage variable, d , has two zones, there will be two derivatives, Eq. (4.16):

$$\frac{\partial d}{\partial \delta^i} = \begin{cases} \frac{\delta_0 \delta^i}{\delta^3} & \delta_0 \leq \delta \leq \delta_c \\ \frac{\delta_0 \delta_f \delta^i}{(\delta_f - \delta_c) \delta^3} & \delta_c \leq \delta \leq \delta_f \end{cases} \quad (4.16)$$

where δ is the acting displacement, as Eqs. (4.8) display.

After the damage reaches the value maximum value of 0.9999, the damage is set to 1, in order to transform the stress to 0. In order to help with the computation, and prevent infinite values of β , when the displacement in Mode I is smaller than 10^{-10} , the model assumes pure Mode II, and uses the values directly from the material properties. Furthermore, the viscosity is used to regularise the damage parameter to prevent discontinuities, with Eq. (4.17) and making sure that the damage in the new iteration, $i+1$, is always equal or higher than in the previous iteration, i .

$$d_v^{i+1} = \frac{\mu}{\mu + \Delta t} d_v^i + \frac{\Delta t}{\mu + \Delta t} d^{i+1} \quad (4.17)$$

With the viscous regularized damage attained, the stress can be calculated with the damaged stiffness matrix and displacement, which is subsequently used to calculate the full Jacobian matrix that ensures the convergence in the static formulation.

Some state variables were saved, besides the ones utilised to run the UMAT, to later used the data saved for validation and result analysis. The DFT was calculated directly with the area of stress and displacement data and saved to STATEV(5). The total displacement and total stress data were saved in STATEV(3) and STATEV(6), since ABAQUS only records the delamination mode specific data for cohesive elements. For future purposes, the strain rate of the elements, calculated with $\Delta \delta / \Delta t$ and saved to STATEV(4).

4.1.1 UMAT Validation

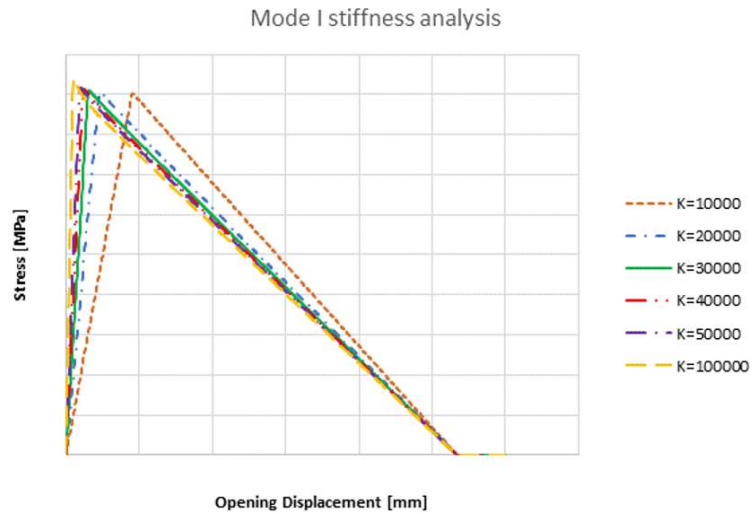
A simple Representative Volume Element (RVE) was created to test the UMAT with the new cohesive law. With the use of viscosity within the UMAT, it's not possible to use the viscosity defines at the meshing of the cohesive elements. Since the CLS uses the complete

UMAT formulation by being mixed mode behaviour, this test will be used to reach the viscosity value with a convergence method.

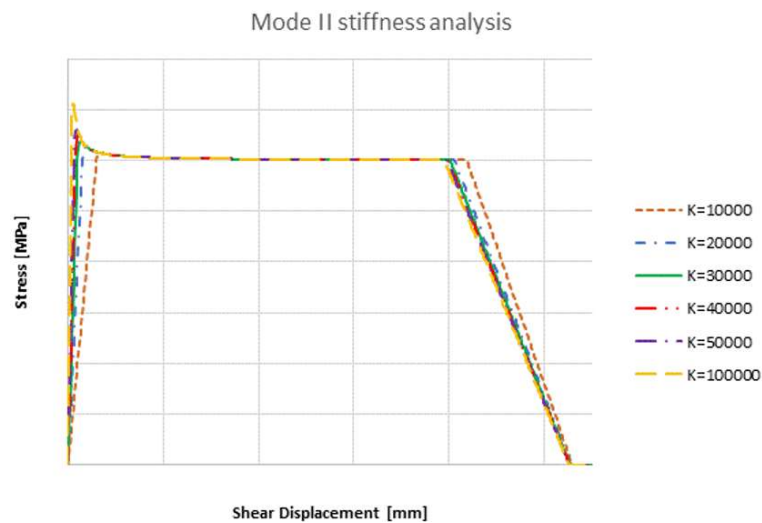
Furthermore, the stiffness of these elements isn't as well adjusted as using the ABAQUS internal formulation, so it is required a new method to find the optimal stiffness. From the literature, this value must be higher than the Young's modulus, but not too high to create numerical issues.

Besides the UMAT, the RVE model has the same modelling aspects as the specimens. The element was loaded to have pure Mode I ($\beta^2=0$), pure Mode II ($\beta^2=\infty$), and mixed mode behaviour ($\beta^2=2.5$) that represents a similar ratio to the CLS test. With the pure mode behaviour, the stiffness value was studied, while the mixed mode was used to compare to a simple triangle law also developed in the UMAT. This mixed mode test also includes the condition of unloading, so a cyclic load was applied to both cohesive laws.

From the stiffness analysis in Graph 31 and Graph 32, it is clear that with the increase in stiffness, an overshoot on the stress starts to appear. On Mode I, this is less intensified and only after 100000 MPa/mm the overshoot is starting to be significant, whilst on Mode II is more significant overall. The errors of these overshoots are reported in Table 9.



Graph 31 – Mode I stiffness analysis on the RVE.



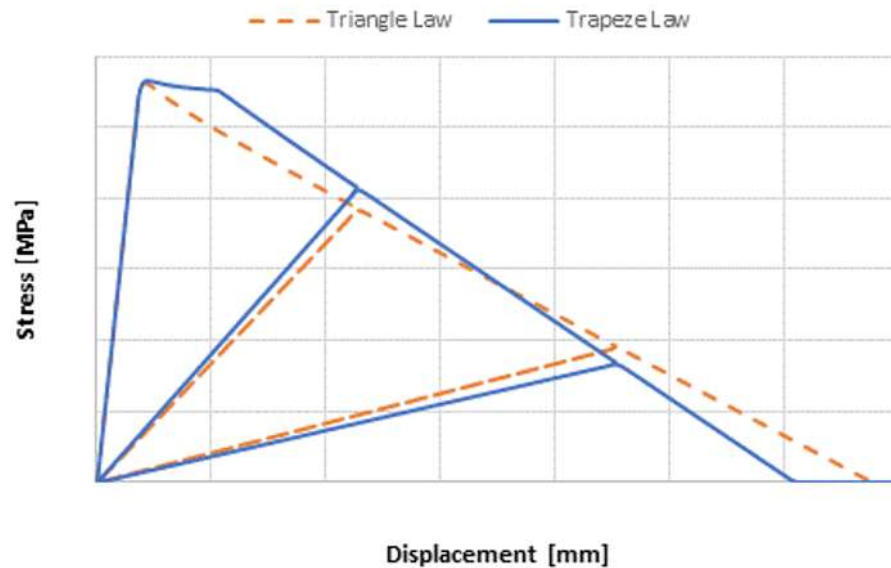
Graph 32 – Mode II stiffness analysis on the RVE.

Table 9 – Overshoot errors of the RVE in percentage

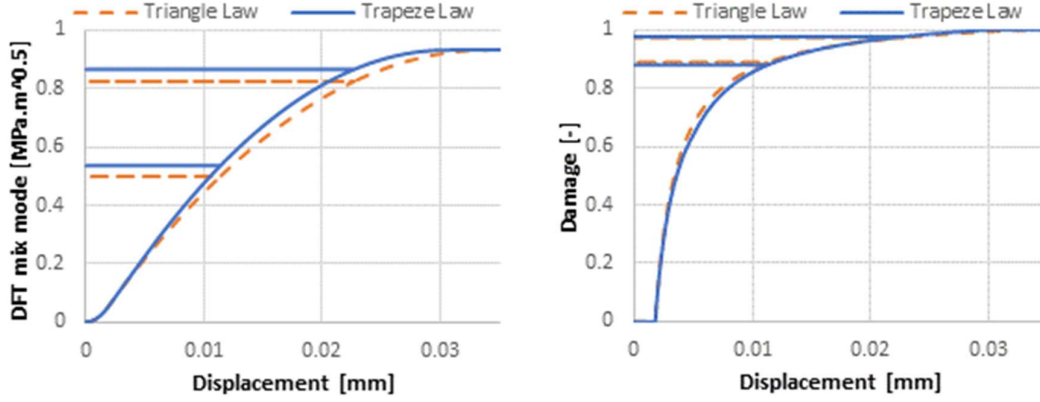
K [MPa/mm]	10000	20000	30000	40000	50000	100000
Mode I	0.219	0.641	1.078	1.490	1.958	4.058
Mode II	2.283	4.338	6.311	8.043	9.996	18.367

From the errors obtained, 30000 was chosen as the value for K since it's 3 times higher than the stiffness, which is determined as sufficient, while maintain an overshoot error small enough in both pure modes. For example, with 40000 MPa/mm the error in stress is already up to 8%, which is deemed too high of an overshoot. To find the value of the viscosity, although the increase in stiffness can lead to a higher computational cost, it ensures a precise result. So, the viscosity convergence method will use the CLS specimen with a stiffness of 100000 MPa/mm, which is shown in Section 5.2.2.

In Graph 33 it's displayed a cyclic test in mix mode to test the trapeze law in both directions of loading, where it clearly shows the reduced displacement to failure on the trapeze law. Also, the loading and unloading was correctly developed. Graph 34 show the consistency of two state variables, the DFT calculated using the area method, and the damage parameter. This was a successful result, since during unloading and reloading, these parameters didn't change. The larger displacement to failure in the triangle law exhibits a later arrival at the max DFT and damage.



Graph 33 – Stress vs Displacement of a cyclic loaded RVE in mix mode I+II for both cohesive laws.



Graph 34 – Consistency checks of the state variables: DFT calculation (left) and Damage (right).

4.2 Dynamic Possibilities

Due to lack of time, dynamic experimental tests were not able to be done. However, a study on the possibilities to model strain rate effect was deemed necessary.

From the literature, the most common approach to model the strain rate is through a curve where the material property changes with the strain rate. But for cohesive material properties, it is not straightforward to attain the aforementioned curve. Consequently, agreeing with the literature, loading rate is used instead of strain rate. This means that the strain rate effect is introduced within the UMAT, where the loading rate is an input, and varies the material properties in accordance.

Some studies utilise the ratio $\dot{\epsilon}/\dot{\epsilon}_{ref}$ instead of the loading rate as the variable of the curve.

The $\dot{\epsilon}_{ref}$ is the reference strain rate corresponding to the static test, while $\dot{\epsilon}$ is the variant strain rate for the different loading rates tests. After an analysis on different specimens using the UMAT created, it was noticed that this ratio is exactly the same as the loading ratio $(\dot{u}/\dot{u}_{ref})$.

The next subsections will describe two methods to incorporate the strain rate effect. One simpler formulation, and one more complex formulation that incorporates a stabilization method when the strain rate changes during the test.

4.2.1 UMAT Simple Strain Rate Formulation

As explained in Section 2.4.2, the cohesive material properties that could have strain rate dependency is the interlaminar strength and the DFT, for all modes of delamination. From this point forward, the properties will be shown without index of the type of mode.

The strain rate dependency of the interlaminar strength can be defined by a Johnson-Cook Law (May 2015), as Eq. (4.18) describes.

$$\sigma_0(\dot{u}) = \begin{cases} \sigma_0^{ref} \cdot \left(1 + C \cdot \log \left(\frac{\dot{u}}{\dot{u}_{ref}} \right) \right) & \text{for } \dot{u} \geq \dot{u}_{ref} \\ \sigma_0^{ref} & \text{for } \dot{u} < \dot{u}_{ref} \end{cases} \quad (4.18)$$

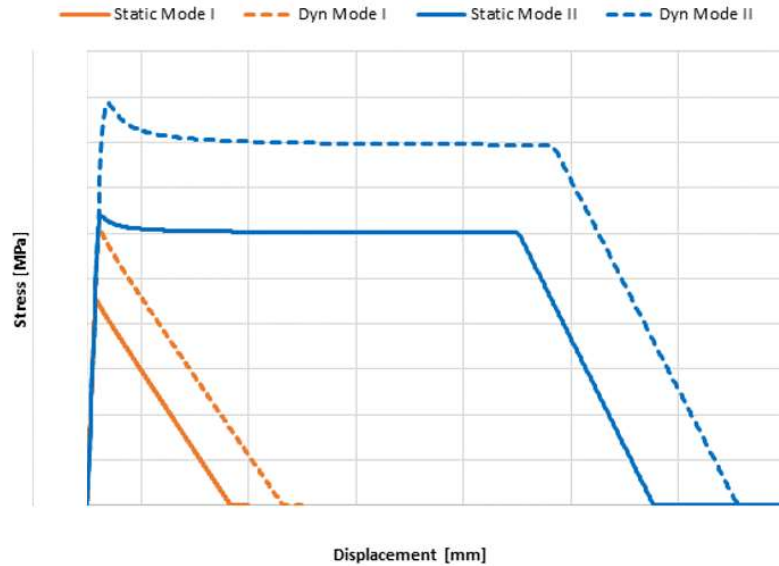
where σ_0^{ref} is the interlaminar strength at the static loading rate, $\dot{u}_{ref}$, and C is a coefficient determined from the experimental results. The relation between σ_0 and the loading rate $\dot{u}$ is a semi-logarithmic plot.

For the DFT($\dot{u}$) there are no clear trends for the evolution, and for simplicity, the strain rate response of the DFT is assumed to be linear on a semi-logarithmic curve, Eq. (4.19).

$$G_c(\dot{u}) = \begin{cases} G_c^{ref} & \text{for } \dot{u} < \dot{u}_{ref} \\ G_c^{ref} \cdot \left(1 + m \cdot \log\left(\frac{\dot{u}}{\dot{u}_{ref}}\right)\right) & \text{for } \dot{u}_{ref} \leq \dot{u} \leq \dot{u}_{inf} \\ G_c^{inf} & \text{for } \dot{u} > \dot{u}_{inf} \end{cases} \quad (4.19)$$

where G_c^{ref} is the DFT at the static loading rate, and G_c^{inf} is the constant value after a reference loading rate $\dot{u}_{inf}$. The constant that defines the slope of the curve, m , can be different than the constant C of the interlaminar strength, and is also obtained through experimental results. The constant m can be either positive for an increase in DFT with strain rate, or negative for a decrease, depending on the strain rate response of the delamination tests. These parameters can be different for both modes. The G_c^{ref} and G_c^{inf} values are used to avoid excessive increase or decrease in the fracture toughness for exceptionally large strain rates. May (May 2015) used the upper bound, G_c^{inf} , equal to two and a half times higher than the reference DFT, G_c^{ref} .

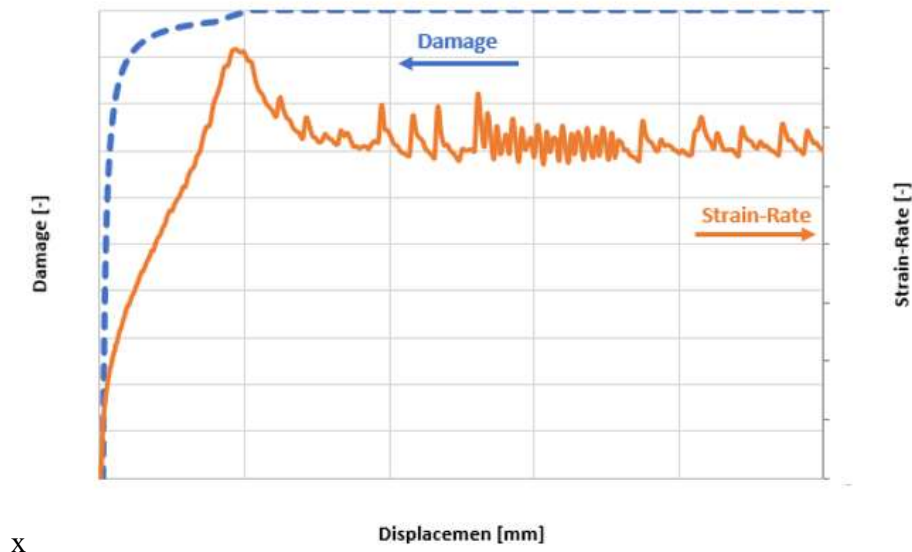
In the UMAT, these formulations were inserted, and the thirteenth material property is the ratio $\dot{u}/\dot{u}_{ref}$. As validation of the UMAT, Graph 35 shows the difference between the static ($\dot{u}/\dot{u}_{ref} = 1$) formulation and the dynamic one ($\dot{u}/\dot{u}_{ref} = 60000$) for both delamination modes applied in a RVE. Without experimental results, C and m of each mode were assumed ($C_I = 3, C_{II} = 4, m_I = 0.1, m_{II} = 0.54$), and the values for the loading ratio were chosen with the static and dynamic loading rate of 1 mm/min and 1 m/s, respectively. The plots were according to what was expected, hence the UMAT simple Strain Rate formulation is validated.



Graph 35 – Validation of both delamination modes using UMAT with Strain Rate formulation in an RVE.

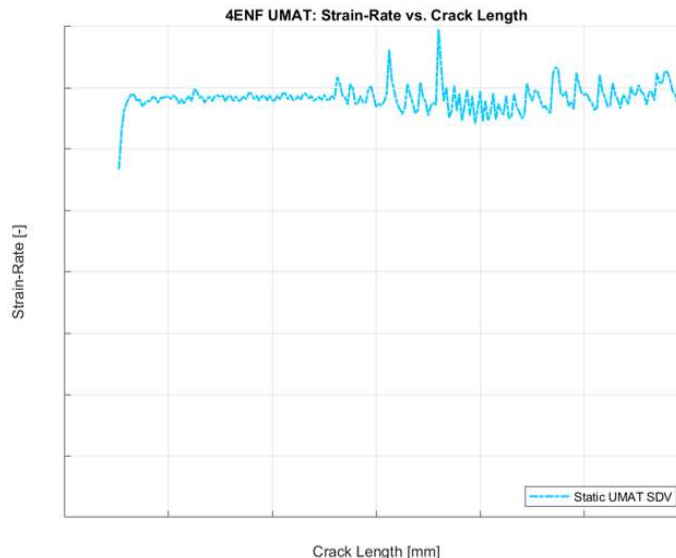
4.2.2 UMAT Complex Strain Rate Formulation

In the UMAT, the strain rate, $\Delta\delta/\Delta t$, was saved in SDV(4), which will be used in this section. For each test, the strain rate during experimental test can be indirectly determined with the numerical model. The strain rate at the time of failure ($d = 0.9999$) was obtained for each element, and the strain rates were displayed as a function of the crack length. Graph 36, SDV data retrieved from the element 500 of the total 580, demonstrates why the strain-rate at failure was used. The strain-rate gets to a maximum close to the max damage. After failure, the strain-rate is irrelevant, before, there is not a clear value of damage where the strain-rate can be retrieved. So, although the max strain-rate value cannot represent the full influence, it can give the upper limit of its effect.



Graph 36 – Cohesive element of Long 4ENF specimen: Damage and SR vs Displacement.

To determine the singular strain rate for the test, after the R-Curve becomes stable, the strain rate at that crack length may be saved, and the Long 4ENF example is displayed in Graph 37. With this information, the interlaminar strength and DFT dependency curves may be calculated using the strain rate rather of the loading rate.



Graph 37 – Long 4ENF numerical UMAT results: Strain-Rate vs Crack Length.

Because of the complex geometries of the specimens, each cohesive element may have a different strain rate, resulting in different cohesive behaviours in different locations of the specimen. Additionally, the strain rate can change in each cohesive element during the test.

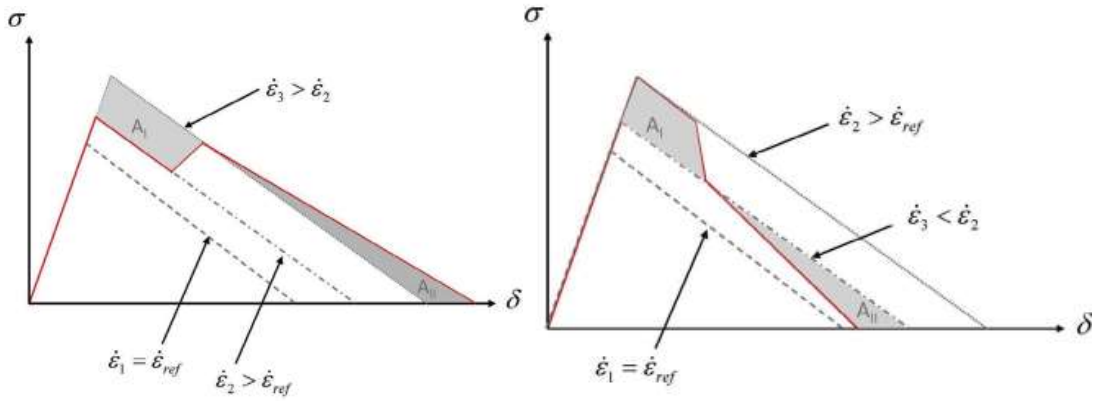
So, a new formulation was created by May (May 2015) that can correct this change in strain rate, updating the DFT and interlaminar strength at every increment. The author utilised a triangle law, so this explanation will be for said law.

The change between a normal triangle law and the new formulation is shown in Eq. (4.20).

$$\delta_f = \frac{2G_c}{\sigma_0} \rightarrow \delta_f = \frac{2(G_c(\dot{\epsilon}) - G_{diss})}{\sigma_0(\dot{\epsilon}) \cdot \delta / \delta_0 \cdot (1 - D)} \quad (4.20)$$

where G_{diss} is the fracture energy dissipated until the current loading time. The expression in the denominator is the current stress of the damaged part of the stress-displacement curve. Graph 38 shows two cases that follow this formulation where the strain rate was changed. The material properties in both cases are assumed to increase with strain rate. The first case (on the left) is when the strain rate is increased, meaning $\dot{\epsilon}_3 > \dot{\epsilon}_2$, where $\dot{\epsilon}_2$ is the initial strain rate. The increase in strain rate leads to an increase in the energy the material sure release. This means that the area A_I that was not dissipated, and the increase in the final displacement with Eq. (4.20) will allow to correct the total energy released with the addition of area A_{II} .

The second case (on the right) shows a strain rate decrease, representing $\dot{\epsilon}_1 < \dot{\epsilon}_2$. The same logic can be applied, but this time the dissipated energy is higher with the new strain rate, requiring a decrease in the final displacement to correct the final DFT value.



Graph 38 – Stress vs Displacement of the cohesive law with updating strain rate parameters during loading: increase of strain rate (left); decrease of strain rate (right)

Within the trapezoidal law defined in the UMAT of this thesis, since the displacement at failure is calculated in relation to δ_c , the updating formulation needs to be applied elsewhere. It is suggested to apply it to the final displacement of the plateau. This leads to a change in the Jacobian matrix, since δ_c will depend on the damage value, and so a revaluation of this derivative would be needed. This investigation was not pursued further due to a lack of time and the absence of dynamic experimental results.

5 Numerical and Comparison

5.1 Numerical Methodology

Within this section the delamination models of the specimens are explained, and then compared to the experimental results. Furthermore, the UMAT that improved the specific behaviour of this material was developed and the results are compared to the CZM within ABAQUS. The strain rate effect implementation is also considered within the development of the UMAT, even without experimental dynamic tests.

All the specimens were created using Python, where the script would be run in ABAQUS, and different models where the difference would be in the cohesive behaviour representation were considered: cohesive elements, cohesive surfaces and VCCT. The UMAT models were made with cohesive elements, so only the material properties change to the user material.

The Python script would create the parts, the materials, the sections, and their assignment, followed by the direction of the material. Necessary surfaces and sets were created in each part. Then generated the assembly, followed by the step for a static/general step and the required history and field outputs. Afterwards created the interaction properties, for example the cohesive surfaces. Constraints were also done using the surfaces created, for example the tie between the cohesive part and the specimen part. The loads were also created using the Python script. Finally, the job was created and run automatically.

After the jobs were completed, it was necessary to retrieve the data from the ODBs. In the same way as to the experimental data, the Force, Displacement, and the Crack Length was all the needed data to implement the ECM. Python scripts were developed to attain this data. The most significant data is the Crack Length, which the method behind measuring the length was: the moment an element (or node for cohesive surfaces and VCCT) reached the damage value of 0.9999, the size of the element was added as Crack Length.

For some models, such as the VCCT, other proprieties were saved, for example the specific mode energies to attain data like the one in Graph 26, and other proprieties such as the FPZ, which counted the number of elements that have damage between 0.0001 and 0.9999. The UMAT ODBs also had the necessary change to attain specific state variable's data.

Four example scripts that attain the ODB data and create the graphs are reported in 0, where B.2 is for the 4ENF ODB reader, B.3 is the 4ENF MATLAB for the ECM of the experimental results, B.4 is the TAST ODB reader, and B.5 is the MATLAB for TAST numerical results.

5.2 Static tests

5.2.1 Models Creation 4ENF

For all specimens the various models, with cohesive elements, cohesive surfaces and VCCT, were created, and the next paragraphs will explain how they were created, and the reason for the choices done throughout the development. Firstly, for the common description of the models, the 4ENF specimen with cohesive elements will be used as an example. Then some specific parts of the rest of tests will also be described.

There are two ways to model the specimens: with solid 3D elements, with 3D shell elements, and with 2D plain strain elements. The latter reduces computational time, are easy to implementation, and the known edge effect, where Mode III can be present, is usually neglected, meaning that the 2D shell elements in plain strain can accurately replicate the tests results. With these 2D shell elements, a two-dimensional deformable part was created for the specimen part and the cohesive part. Furthermore, for the 4ENF specimen, a rigid body representing the fixed and loading rollers was created with the wire option. These rigid bodies have a centre “*Reference Point*” to be used for boundary conditions. The sizes of the parts are taken from the dimensions of Figure 48 of the Annex A. The cohesive thickness was set at 0.01 mm since the Teflon insert as a similar thickness (Low, Johar et al. 2021). The necessary planes and subsequently partitions that will be used to create the surfaces and sets for the interactions and the outputs, as seem Figure 39.



Figure 39 –Long 4ENF numerical model: Specimen part with planes and partitions.

The next step was the creation and the section assignment of the materials. Only the inertia and a point mass were inserted to the rigid bodies to help the computation. These values were set low to not affect the overall results. The elastic material properties were set homogenously to represent the 3D woven angle interlock material (Gerlach, Siviour et al. 2012). The width of the specimen inputted within the section creation was set at 1 mm. This means the force results need to be multiplied by the width of the real specimen (25 mm). For the cohesive part, being a cohesive type of section, the response was established with “*Traction Separation*”, the value for the “*Initial Thickness*” is very important. By setting the value at 1, the strain values will be equal to the displacements of the nodes.

The assembly of all the parts is shown in Figure 42 for the 4ENF specimen. The assembly is dependent, meaning the mesh will be done for each part separately. Within the assembly is where the surfaces and sets and created to later be used in interactions, constraints, outputs, and loads. In red are the initial crack lengths. A reference point between the two loading rollers is created to simulate the loading assembly, where the two rollers are kinematically connected to that reference point that will have the displacement load.

The static analysis, the step created after the initial step was the type “*Static, General*”, using the large-displacement formulation by setting the “*Nonlinear*” on, which is important for non-linear formulations such as the cohesive behaviour in cohesive surfaces. This behaviour also requires a large number of increments of 10^6 , and a small minimum increment size of 10^{-20} . The step time was set equal to the amount of displacement necessary for each specimen. The outputs of interest are the history outputs, one for the loading reference point, where the displacement and reaction force were saved. The other one is the “*SDEG*” (scalar stiffness degradation) for cohesive elements, “*CSDMG*” (scalar stiffness degradation for

cohesive surfaces) for cohesive surfaces and VCCT, the latter also had the variables “ENRRT” which save the strain energy release rates for each direction. The field output is just used for TAST to obtain the strain and stress along the crack line, otherwise it just shows the variables in the ODB for visualization of the test and crack advance.

The next step in the codes is to mesh the different parts. The specimen part was meshed with the element shape “*QUAD*”, and the type was “*CPE4*” in the standard element library which do not use the reduced integration, since its reduced stiffness can cause spurious deformation. Furthermore, this element is a bilinear plane strain element. The rigid bodies only type is the “*R2D2*” which is a two-node two-dimensional linear rigid link that is usually used for plane strain problems.

As for the cohesive part (cohesive surfaces and VCCT models do not have this part), the element type is “*COH2D4*”, which are in the family of cohesive elements as a four-node two-dimensional element. This element requires viscosity to help the computation. The value of viscosity of the cohesive elements was initially set at 10^{-8} , a small value. If there is difficulty in convergence, this value was increased until the convergence of the model was obtained.

A similar convergence method was done to reach the mesh size for the specimen part, especially for cohesive surfaces and VCCT. The cohesive or fracture behaviour must use “*small sliding*” formulation which considers that the surfaces can undergo arbitrarily large rotations, but that during the analysis, a slave node will interact with the same local area of the master surface. The degree of refinement for the master surface must therefore be given more consideration. The smoothly varying master surface normal and the local tangent planes that are formed with it are crucial to the success of a small-sliding analysis. The deformation and rotation of the master surface might reorient the local tangent planes, causing them to be a poor approximation of the master surface. This difficulty can be mitigated by utilising a more refined mesh on the master surface, which provides more element faces to regulate the motion of the tangent planes. This refinement was more predominant in specimens that have bending in the models that use cohesive surfaces or VCCT, leading to a high number of elements, and so, costing more computational time.

The mesh in the thickness direction of the elements in all models was set at eight elements with a double direction bias to have more refinement close to the edges. The element size in the longitudinal direction for the specimen part is reported in Table 10 for all models, values reached decreasing the size of the elements until convergence was met.

Table 10 – Element sizes in the longitudinal direction of the specimen part for each type of model

Test specimen Type of model	Long 4ENF [mm]	Short 4ENF [mm]	CLS [mm]	ELS [mm]
Cohesive Elements	0.25	0.5	0.5	0.25
Cohesive Surfaces	0.1	0.1	0.5	0.2
VCCT	0.1	0.25	0.25	0.2

The cohesive elements have a specific length, originated from the Cohesive Zone Length, l_{cz} . Using the cohesive material properties, and the Rice (Rice 1980) and Falk (Falk, Needleman and Rice 2001) model which is the most used model according to Turon et al. (Turon, Dávila et al. 2007), the l_{cz} for Mode I and Mode II is calculated with Eq. (5.1) and (5.2). The element deletion is also set to “No” to reduce instabilities that may occur.

$$l_{cz}^{Mode I} = \frac{9\pi}{32} E_3 \frac{G_{Ic}}{(\bar{\tau}_{33})^2} \quad (5.1)$$

$$l_{cz}^{Mode II} = \frac{9\pi}{32} (G_{13}) \frac{G_{IIc}}{(\bar{\tau}_{13})^2} \quad (5.2)$$

To represent the crack initiation process correctly it is necessary between 3 and 10 elements in the l_{cz} . Thus, the smaller value of l_{cz} and 10 elements to represent it will make sure that the cohesive model is correctly characterised. This resulted in an element size of approximately 0.25, which ensures a foreseeable number of elements according to the size of the cohesive part (four times the length of the cohesive part).

In Figure 40 it's an example of the mesh in the complete assembly of the cohesive element model of the Long 4ENF specimen.

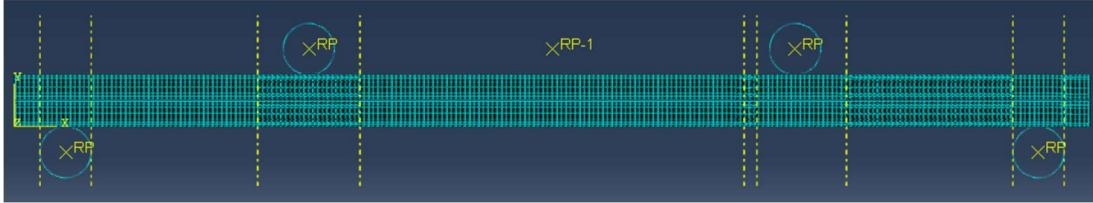


Figure 40 – Long 4ENF numerical model: Mesh of the complete assembly for cohesive element type model.

Besides the cohesive behaviour, which will be discussed in section 5.2.1.1, other interactions and constraints are at play. The common interaction between all models is a surface-to-surface frictionless penalty contact on the pre-crack surfaces since the Teflon insert should reduce the friction to a minimum. The contact between the rollers and the 4ENF specimen part was created with a surface-to-surface contact. The “*finite-sliding*” formulation was employed as the default option. Without knowing the correct value for the friction coefficient, it was necessary to assume a common value, in this case 0.15.

The 4ENF specimen requires a coupling between “*RP-1*” and the two loading rollers, that are kinematically connected as explained before. All the degrees of freedom were constrained. On the models with cohesive elements, the specimen part and the cohesive part are tied together. The interactions present in the 4ENF test are shown in Figure 41.

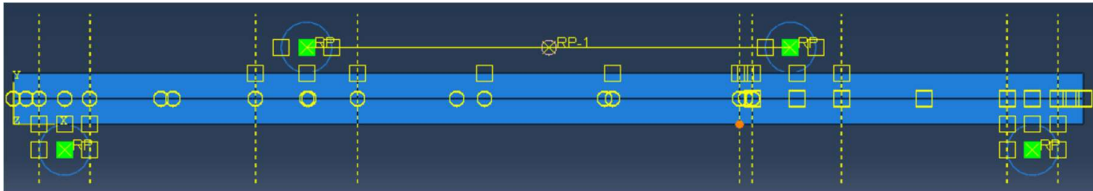


Figure 41 – Long 4ENF numerical model: Interaction module.

The loads are specimen specific. All the models will use displacement control, with the type “*Displacement/Rotation*” using a “*Ramp*” amplitude. The 4ENF specimen bottom rollers are *encastre*, while the top rollers are moved through the application of the displacement load at the “*RP-1*”. The loading of this point is created in the vertical direction, with enough

displacement to realise the full numerical analysis (crack propagation for 4ENF, CLS and ELS tests and failure of the cohesive part for TAST). The horizontal displacement is set to 0, and the rotation of the point is free, meaning that the collective simulated part of the loading rollers can freely rotate, making sure that the force applied by each roller is the same, as seen in Figure 42.

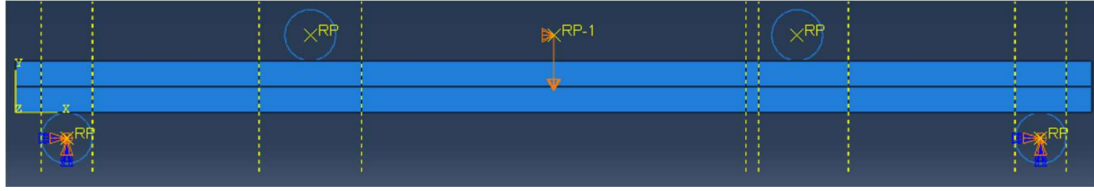


Figure 42 – Long 4ENF numerical model: Loads.

5.2.1.1 Cohesive Behaviour in the Models

The last missing modelling component is the damage behaviour. As mentioned before, the damage behaviour will be represented as cohesive elements, cohesive surfaces and VCCT. Section 2.4.1.2 went in detail about the CZM. And the chosen approach was using a quadratic stress initiation criterion, a B-K mixed mode behaviour, and a simple bilinear (or triangle) cohesive law. The next paragraphs will explain the implementation of the CZM in the three different ways of representing the damage behaviour.

The models with the cohesive elements, it is just necessary to use the cohesive material properties, which are reported in Table 8. The nominal stresses are registered in “*Quads Damage*” (defines a quadratic stress damage initiation), while the sub option “*Damage Evolution*” saves the DFT for all modes. For that it is necessary to select the type of damage evolution (energy or displacement), the type of softening (linear, exponential, or tabular), the degradation (maximum or multiplicative), the mixed mode behaviour (B-K, mode-independent, tabular, or power law) and the mode mix ratio (energy or traction). The first option within parentheses for each variable is the one selected. The last sub option is the “*Damage Stabilization Cohesive*” that registers the viscosity coefficient. This value was initially set to 0.0001. The convergence method wasn’t necessary since the viscosity of the material is coupled with the viscosity of the elements, so only one needs to change to reach the result. The last material property, the stiffness of the cohesive material, is inserted in the “*Elastic*” material behaviour with the type “*Traction*”.

The cohesive surfaces model represents the damage behaviour within a surface-to-surface contact interaction. As previously mentioned, the cohesive surfaces use the “*small sliding*” formulation. The interaction property is where the cohesive behaviour is established. Since there aren’t elements to make sure penetration between the two specimen parts of the assembly, it is necessary a normal and tangential behaviour, which define “*Hard contact*” and a penalty friction formulation with a friction coefficient of 0.15. Then the “*Cohesive Behaviour*” contact propriety registers the stiffness, and the “*Damage*” contact propriety encapsules the damage “*Initiation*” with a quadratic traction criterion, the damage “*Evolution*” which inputs are the same as in the cohesive elements damage evolution, and the damage “*Stabilization*” that saves the same viscosity coefficient. All these properties used the same values as the cohesive elements.

Only the surface where the crack will propagate is deemed necessary to apply this interaction. This is important to specify because the VCCT formulation is different. This formulation selects the entire surface, including the pre-crack. To define the where the pre crack is, the group of nodes of the surface where the crack will propagate was selected in the “*Bonding*” tab of the interaction. Continuing the comparison to the cohesive surfaces,

the damage behaviour, instead of using “*Cohesive Behaviour*” and “*Damage*”, VCCT uses “*Fracture Criterion*” with the type “*VCCT*”, using the B-K mixed mode behaviour with the corresponding parameter and DFT for each mode. The tolerance was also set to 0.05, a reduced value to the default of 0.2, to ensure a more accurate result. To finalise the cohesive interaction, a crack of the type “*Debond using VCCT*” was created in “*Engineering Features*” within the assembly that defined the initiation step with the same step where the loading begins.

5.2.1.2 Specific Model Differences on Other Specimens

The other specimens have a relatively similar model. The main differences are highlighted in this subsection. TAST, CLS, and ELS will be order of presentation of these differences.

The assemblies of the TAST model have reference points that simulate the centre of the grips that pull the specimen, as shown in Figure 43. This means that the gripped zone of the specimen is not necessary to be modelled. This point had a kinematic coupling to the side of the specimen that will be pulled.

The TAST models can’t use the VCCT model since no initial crack is present. Their number of elements in the crack line are the most important, and both cohesive elements and cohesive surfaces have 50 elements on the specimen on that edge. To accurately attain the strain and stress along the crack path no damage modelling can be present, otherwise the stress in the elements tend to go to zero. So, a new model without damage was created, and the models with cohesive behaviour are used to determine the moment of failure. Then the data is acquired from this new model. This model has a very refined mesh on the crack line, with 200 elements in the 8 mm between the indents, to try to capture a complete stress distribution.

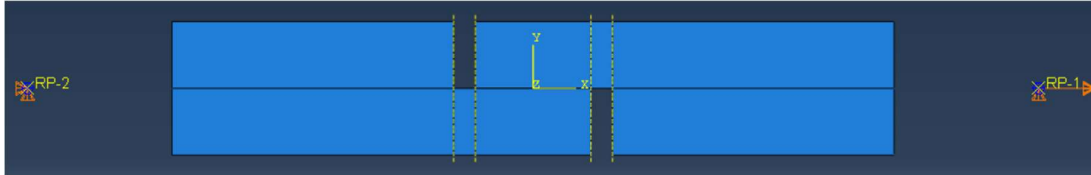


Figure 43 – TAST numerical model: Loads.

The CLS specimen has the same kinematic coupling as the TAST between the reference point and the end of the longer arm to impose the displacement, as seen in Figure 44. This figure also shows how a VCCT interaction is visible within the interaction module.

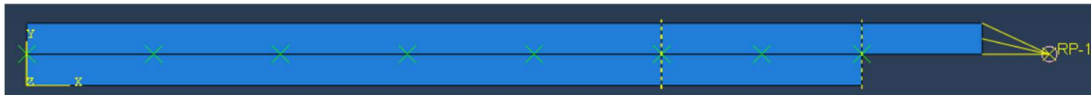


Figure 44 – CLS numerical model with VCCT: Interaction module.

The CLS is also a tensile test, thus, the load is applied in the reference point with a horizontal displacement, and the other tip of the specimen is *encastre* as shown in Figure 45.



Figure 45 – CLS numerical model: Loads.

Meanwhile, the ELS has rigid bodies that behave as the boundary conditions in an experimental set up. On the left of Figure 46, the two rigid bodies were tied to the specimen

to replicate the movable grip, and on the right, there is the rigid body tied to the specimen to introduce the load. This approach was used to better represent the test since the grip is movable in the horizontal direction, and the size of the loading body is important for the correction factors. A tie is present between the rigid bodies and the ELS specimen, to simulate for example the bonding of the loading part.

The ELS test only has a vertical displacement on the loading part, fixing the rotation and horizontal displacement, while the rigid bodies that simulate the grips have the rotation and the vertical displacement fixed, meaning that the grips can move horizontally, as explained in the analytical model, as seen in Figure 46.

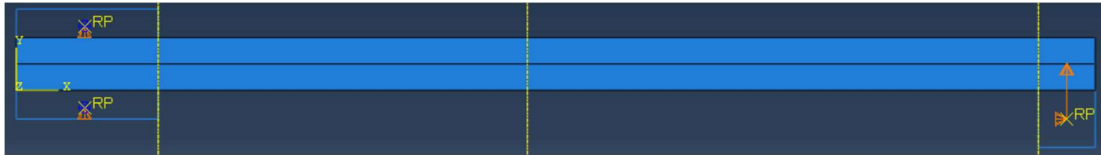
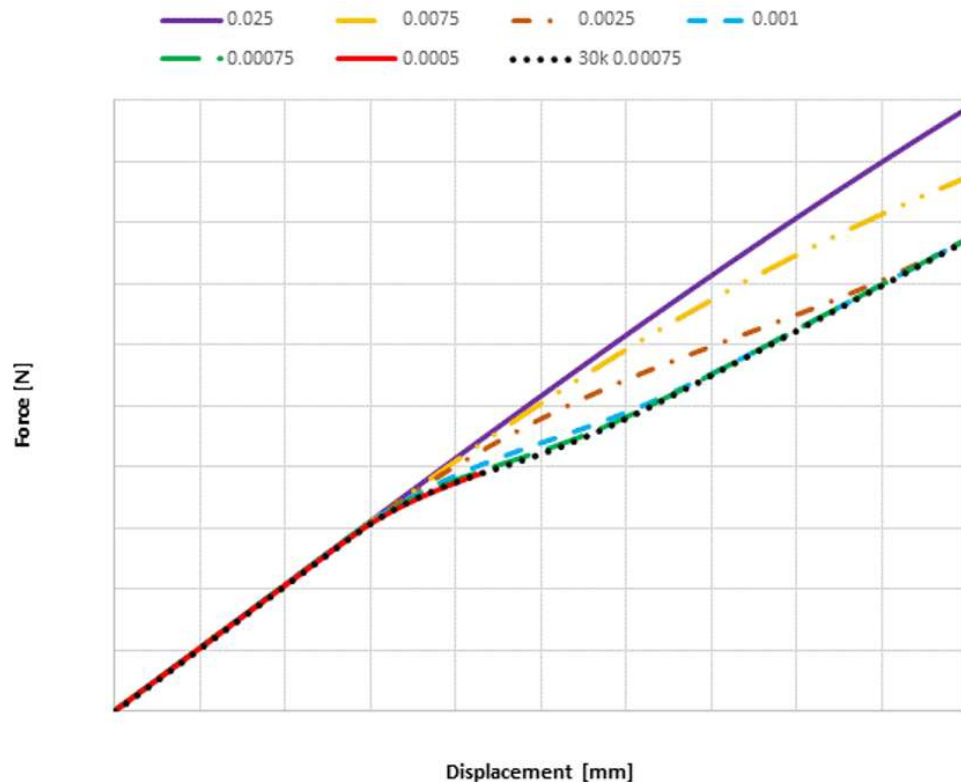


Figure 46 – ELS numerical model: Loads.

5.2.2 Viscosity Convergence Method for UMAT

Graph 39 shows the numerical results where only the viscosity is changed to the values in the legend. From this graph it's possible to conclude that at the 0.00075 viscosity the test has converged, since with a lower viscosity value the result follows the same curve. Table 11 shows that the decrease in viscosity increases the computational time rampantly, which supports the decision of using the highest value of viscosity that meets the expected result. To complete this analysis, a test with the selected stiffness and viscosity is displayed on Graph 39 to confirm the convergence, and Table 11 also demonstrates the decrease in computational time with decrease in stiffness, proving the reduction of numerical issues.



Graph 39 – UMAT viscosity convergence results on the CLS test.

Table 11 – Computational times of the CLS viscosity convergence analysis with $K=100000$

Test's viscosity	0.025	0.0075	0.0025	0.001	0.00075	0.0005	0.00075 ($K=3 \cdot 10^4$)
Time (s)	47	80	423	2320	7311	20295	918

5.3 Static Results

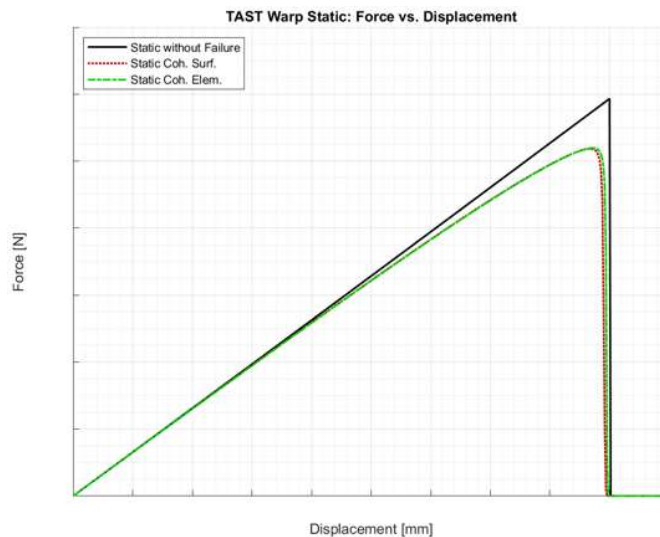
In this section, the results from each model will be presented in conjunction with the experimental results with the 95% confidence curve. The exceptions are some results such as the stress and strain along the crack line of the TAST, and the CLS results, since only one experimental result was completed. Furthermore, the ELS specimen results will be shown for the sake of completeness, even though there aren't experimental results, but they were still planned to enter the delamination analysis.

5.3.1 TAST Warp Direction

In preliminary simulations, it was noted that the change in the Mode II DFT value didn't change the failure load of the TAST result. So, the test failure load is determined mainly by the interlaminar shear strength.

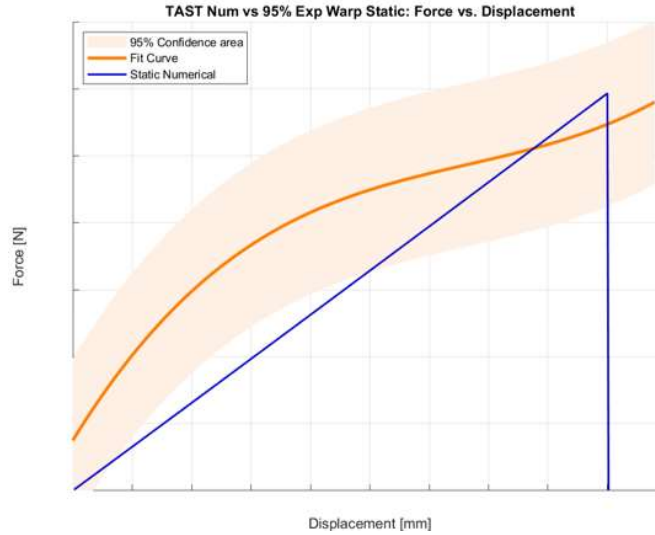
The analysis is performed on a non-damage model to attain the stress along the crack line correctly, otherwise it reduces the stress of the crack plane with the introduction of damage. The models with damage were utilised with the purpose of knowing at what displacement the non-damage model should fail. Then, the full analysis is on the non-damage model.

As an example, the Load vs Displacement plot of the cohesive element, surface, and non-damage model (already reduced to the selected frame) is shown in Graph 40. Either the cohesive elements or the cohesive surfaces can retrieve the displacement of failure, but the first option was selected.



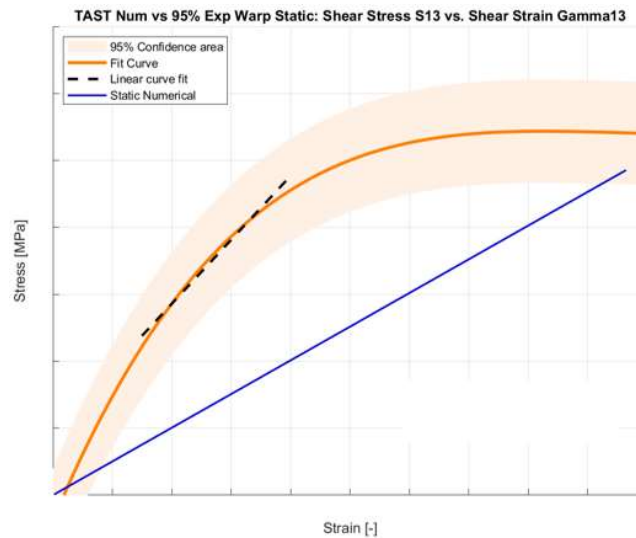
Graph 40 – TAST warp direction numerical model with and without damage: Load vs Displacement.

Afterwards, the non-damage model is compared with the experimental results in Graph 41. The force at failure was fairly accurate. Since the experimental analysis used the DIC measurement, with relatively high values of projection error, the displacement of the numerical models was multiplied by 20, in order to have an easier comparison. Besides the projection error, the shear damage across the entire material wasn't modelled (only on the cohesive zone of the crack line), which can lead to a higher global displacement of the specimen. Furthermore, without the global shear damage, the curvature of the experimental plot isn't present in the numerical models.



Graph 41 – TAST warp direction numerical and experimental results: Load vs Displacement.

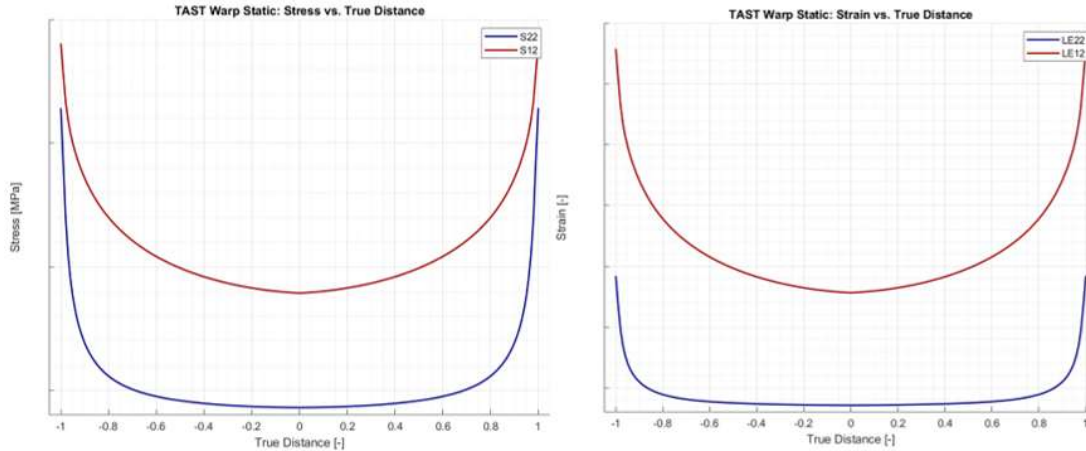
The next comparison is displayed in Graph 42, where the Shear Stress vs Shear Strain was plotted to attain the slope which should be equal to the shear modulus. The numerical value had an error of just 0.6%, while the experimental had an error of 87.7%. The initial linear slope of the curves is used for this method. This however, as explained before, cannot be used truthful, since the projection errors are too high, leading to miscellaneous results.



Graph 42 – TAST warp direction numerical and experimental results: Shear Stress vs Shear Strain.

The next plots represent the stress and strain state across the crack line, Graph 43. These results were taken at the frame of failure and represent the shear stress/strain as “ S_{12}/LE_{12} ”

and the opening mode stress/strain “ S_{22}/LE_{22} ”. Comparison to the experimental results is impractical due to the high projection errors, but these results are still useful for an understanding of the expected purpose of the TAST.



Graph 43 – TAST warp direction numerical results: Stress and Strain vs True distance of the crack line.

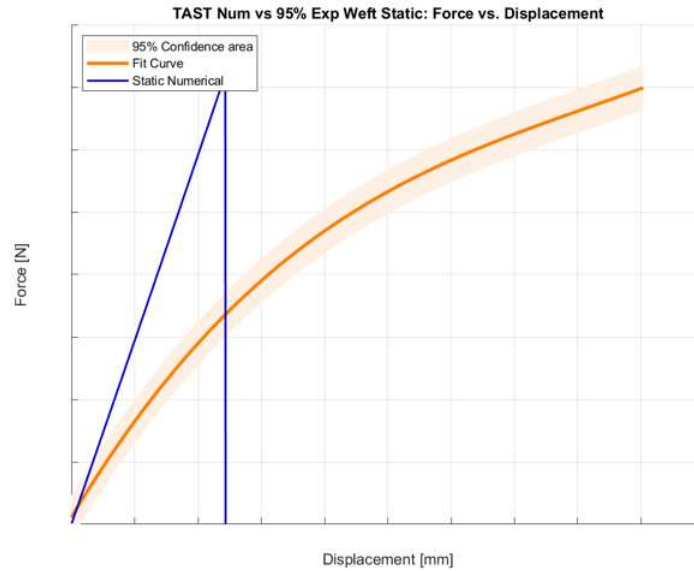
The average, max, min, and average normalised values according to the interlaminar shear strength of the stress plots are reported in Table 12. For an interlaminar strength in warp direction of 1 MPa, when the average stress across the plane reaches a similar value is when the TAST specimen fails. The average opening stress is insignificant compared to the shear stress, confirming the pure shear effect of the TAST.

Table 12 – TAST warp direction numerical results: Max, Min, and Average of the stresses on the crack line.

Type of Stress	Max value	Min value	Average value
Shear S_{12} [MPa]	2.341	0.655	0.955
Opening S_{22} [MPa]	1.903	-0.118	0.052

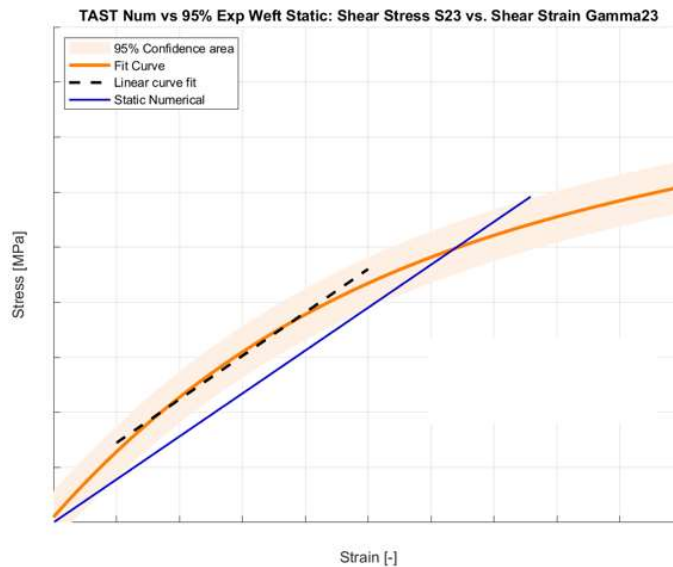
5.3.2 TAST Weft Direction

The same analysis as in the warp direction tests can be done for weft direction. Since in these experimental results the projection errors were within reasonable values, no displacement correction was introduced in the numerical plot. The identical max force was reached with numerical results, and, as shown in Graph 44, the global shear damage behaviour is clearly present in experimental curve. The difference in the slope and displacement between the experimental and numerical plot could be then explained with the absent global damage model, which can lead to a lowering of the global stiffness during the test.



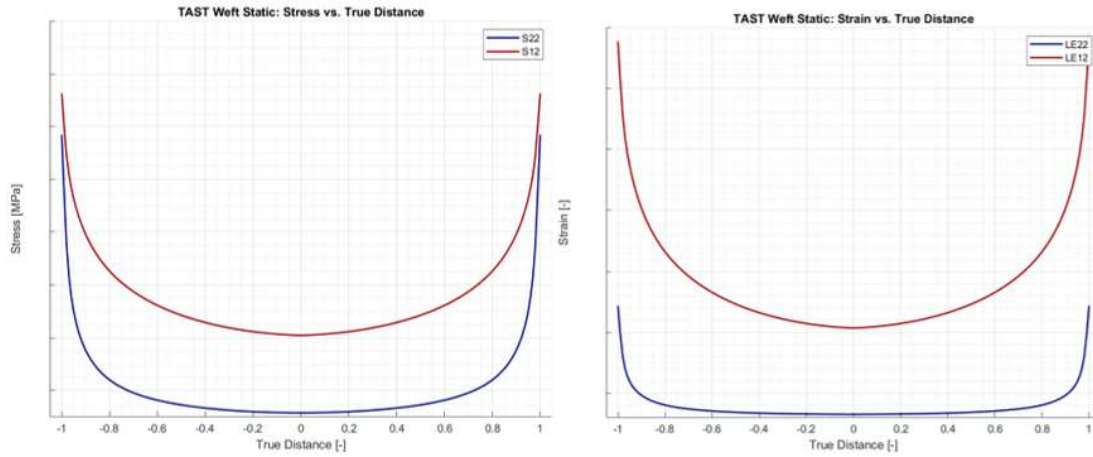
Graph 44 – TAST weft direction numerical and experimental results: Load vs Displacement.

The shear modulus of the weft and thickness direction resulted in an error of 0.93% for the numerical models, and an error of 2.12% for the experimental results, as displayed in Graph 45, concluding that with a good DIC analysis, the TAST can be used for the identification of the shear modulus and strength.



Graph 45 – TAST weft direction numerical and experimental results: Shear Stress vs Shear Strain.

Although the DIC projection errors were good, the weft tests lead to a high roughness crack line. Consequently, the DIC strain analysis along the crack line before failure gives miscellaneous results. Nevertheless, the numerical results were attained, and the plots are displayed in Graph 46, with the max, min and average values of the stress plot are reported in Table 13.



Graph 46 – TAST weft direction numerical results: Stress and Strain vs True distance of the crack line.

The same conclusions as the warp direction numerical results can be reached for the weft direction, with the normalised interlaminar strength in the weft direction being 0.583 MPa. So, when the average stress along the crack line reaches this value, the specimen fails. Furthermore, the average opening stress is once again insignificant compared to the average shear stress.

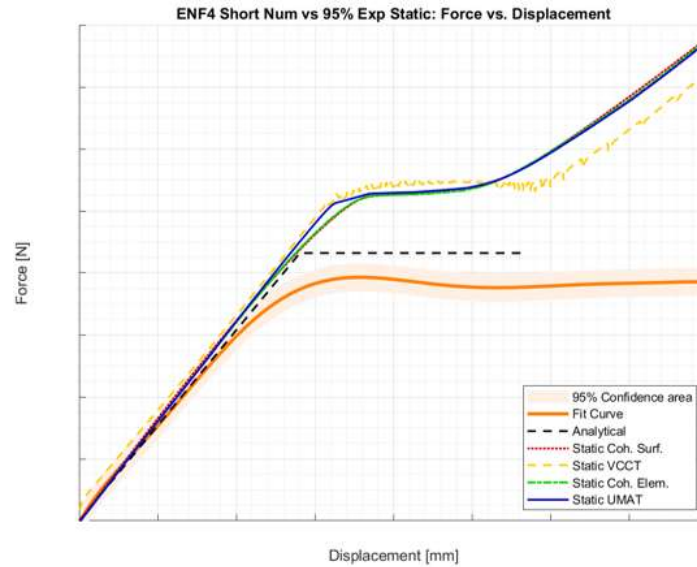
Table 13 – TAST weft direction numerical results: Max, Min, and Average of the stresses on the crack line.

Type of Stress	Max value	Min value	Average value
Shear S12 [MPa]	3.218	0.595	1.015
Opening S22 [MPa]	2.769	-0.242	0.0226

5.3.3 Short 4ENF

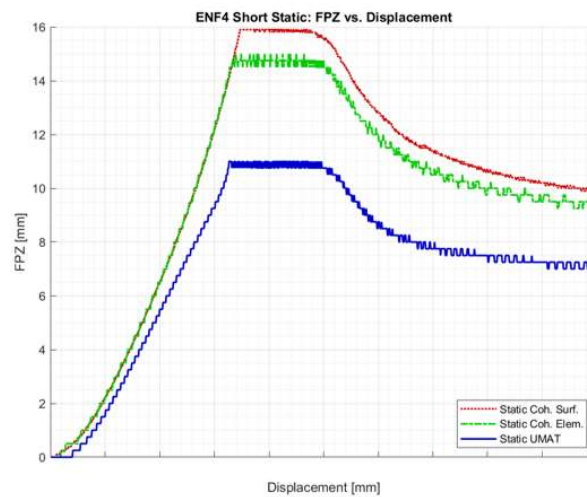
In this specimen, the objective was just to test the set up, and check the consistency of this geometry. Since the Long specimen is the main test, the values attained from said experiment were used in the models for the Short 4ENF. Without any crack data, only the Load vs Displacement of the numerical models can be compared with the experimental results. And for the sake of completeness, the numerical FPZ vs Displacement and R-Curve will also be reported.

Starting with the Load vs Displacement plots, Graph 47 shows a clear difference the force of the plateau. This is due to the difference value of DFT used. For the Long 4ENF the normalised DFT through analytical equation, Eq. (3.8), is $1 \text{ MPa} \cdot \text{mm}$ while for the Short 4ENF is roughly $0.82 \text{ MPa} \cdot \text{mm}$. This can result from many factors, such as a “size effect” of the test’s geometry, a more localised damage in the specimen due to its short length making it fail prematurely, a change in the failure mode, or even the friction coefficient introduced in the models being too high. The latter conclusion can be supported by Graph 3 (Parrinello 2018).



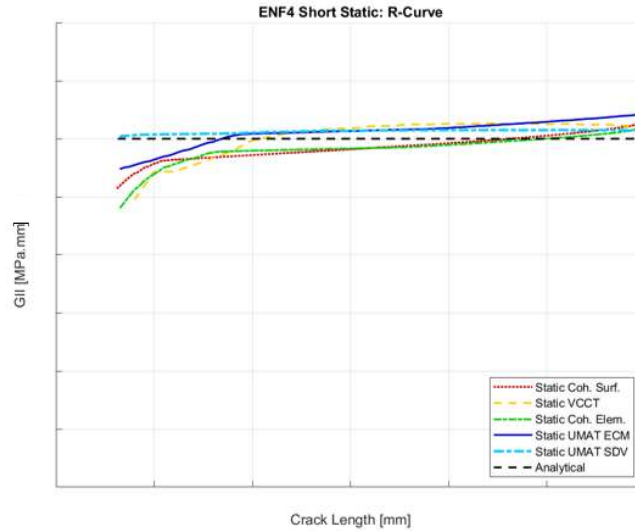
Graph 47 – Short 4ENF numerical, experimental, and analytical results: Load vs Displacement.

Graph 48 displays a clear decrease in FPZ during propagation (where the plateau exists in both graphs) for the UMAT model. This corroborates the less diffuse damage of the UMAT model compared to the other numerical models, observed in Graph 34.



Graph 48 – Short 4ENF numerical results: FPZ vs Displacement.

The R-Curve for the numerical models is displayed in Graph 49. Every model obtains a similar curve through the ECM, around the inputted value. The UMAT has two ways of reaching the R-Curve. The first is using the ECM, and the second is using the State Dependent Variable (SDV) that calculates the energy released with the area of the traction-separation plot, obtained within the UMAT to retrieve directly the DFT per cohesive element. In Annex E, the possible “size effect” of the variance in the distance of the top rollers is investigated. Results show that even with a difference in the plateau of the Load vs Displacement graph, the final R-Curve is still similar using the ECM (Experimental Compliance Method).

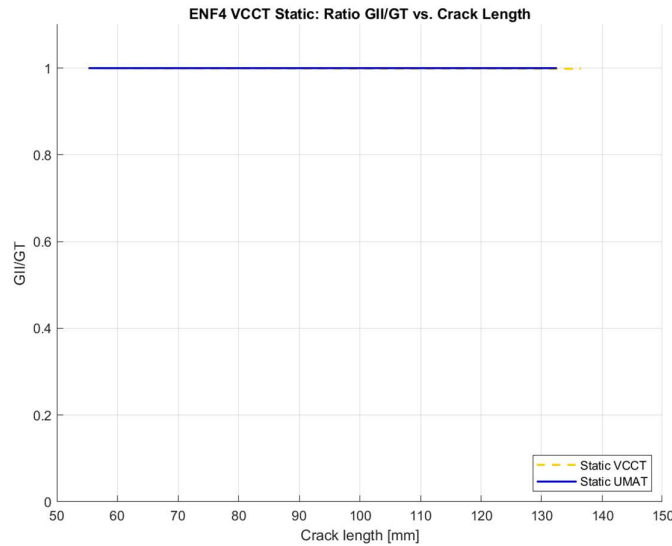


Graph 49 – Short 4ENF numerical results: R-Curve.

5.3.4 Long 4ENF

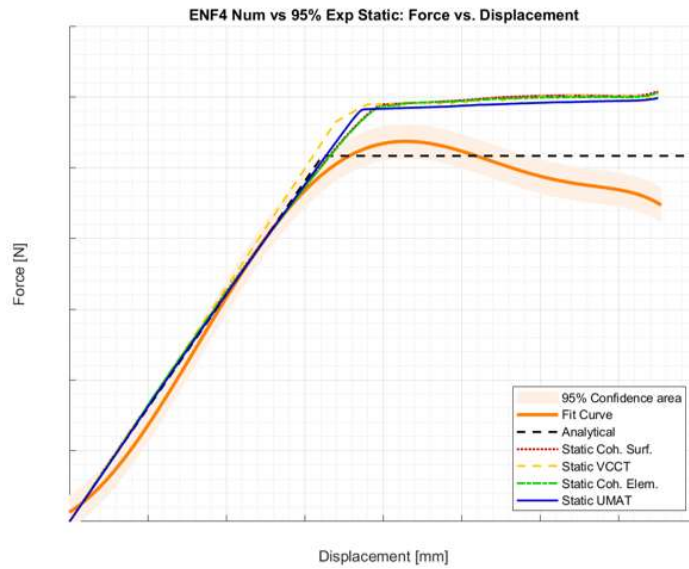
The 4ENF tests with a higher length were created with the objective of decreasing the friction effect of this specimen.

Firstly, the 4ENF for both sizes and the ELS specimens all have the exact same mixed mode ratio plot, with a constant value of 1, displayed in Graph 50, which confirms the mode II behaviour.



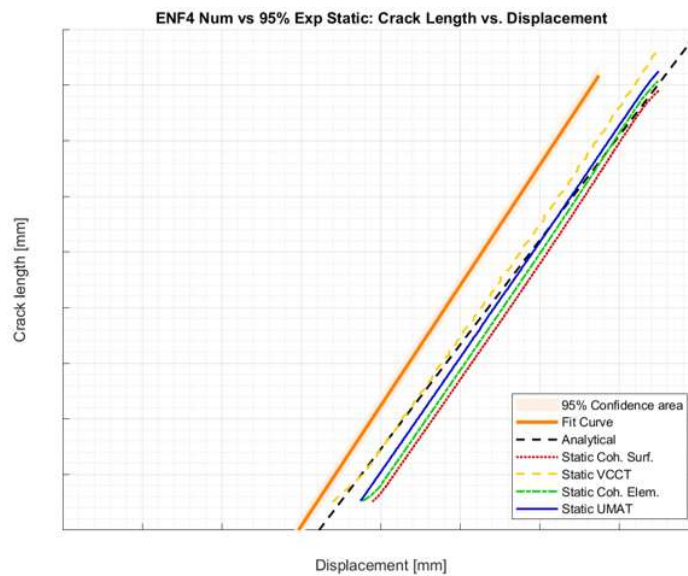
Graph 50 – Long 4ENF numerical results: Ratio G_{II}/G_T vs Crack Length.

The next plot is the Load vs Displacement with the numerical, experimental with 95% confidence zone and the analytical results, Graph 51. The plateau of the numerical models is at the same value of force, but still higher than the experimental results. The difference between the plateaus in this specimen is around 1000 N, while for the shorter specimen is roughly 2000 N, so the friction or size effect were diminished with the longer sample. Reducing the friction in the models or increasing the size of the specimen could lead to more accurate results.

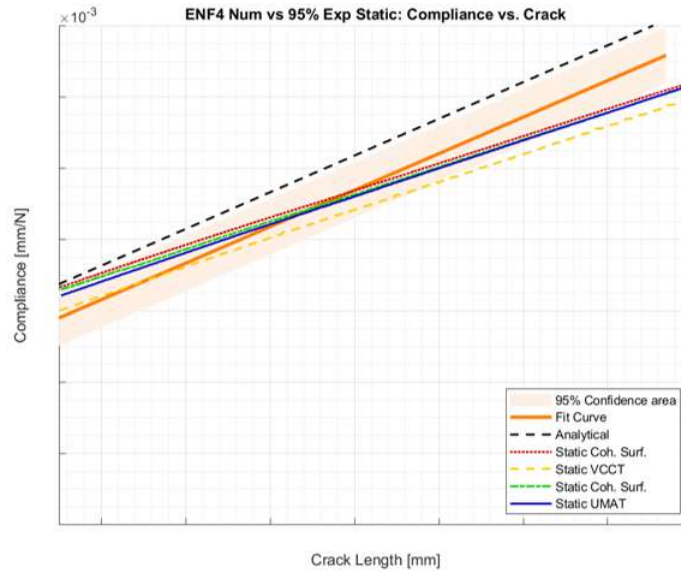


Graph 51 – Long 4ENF numerical, experimental, and analytical results: Load vs Displacement.

Then, the Crack Length vs Displacement and Compliance vs Crack Length plots are reported in Graph 52 and Graph 53, respectively. The crack length is similar across all numerical models, analytical and experimental. Since the numerical models have a higher force and the crack plots are similar, the compliance slopes decrease.



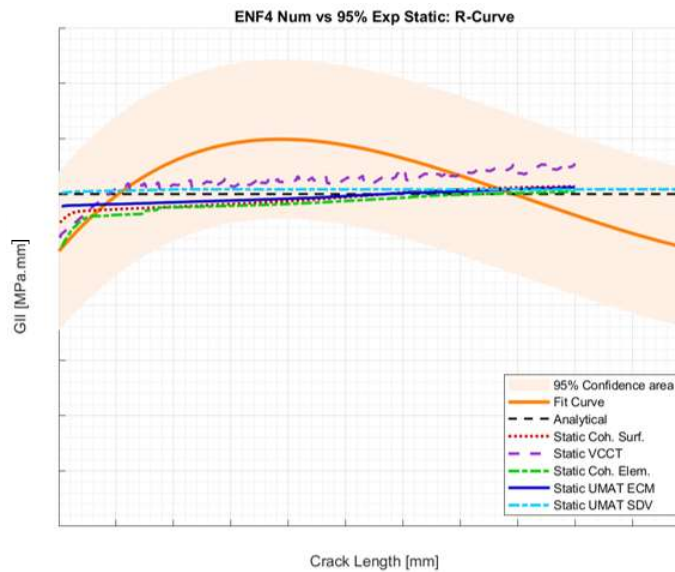
Graph 52 – Long 4ENF numerical, experimental, and analytical results: Crack Length vs Displacement.



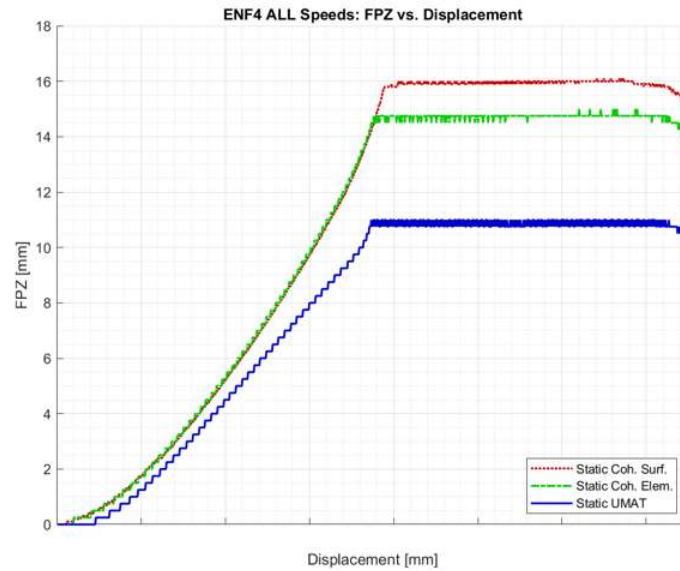
Graph 53 – Long 4ENF numerical, experimental, and analytical results: Compliance vs Crack Length.

The difference in the slope of the numerical models compensates the higher force value of the plateau. This leads to an accurate prediction of the R-Curve, displayed in Graph 54, where all the numerical models could reproduce the R-curve around the average value attained from the experimental results. This agrees with the analysis done in Annex E.

Furthermore, the UMAT was able to reduce the FPZ, as Graph 55 shows, for the complete test range. This reduction makes the Load vs Displacement during the initial propagation have a higher stiffness, this means, less damage introduced in the whole model. With less damage, the initiation values of DFT are higher for the UMAT than for the other numerical models. After initial propagation, all models tend to the stable propagation value for the DFT.



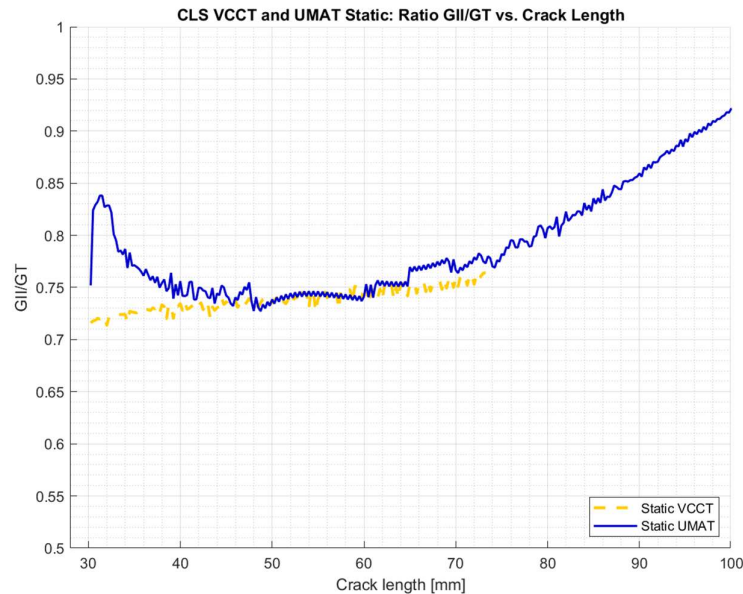
Graph 54 – Long 4ENF numerical, experimental, and analytical results: R-Curve.



Graph 55 – Long 4ENF numerical results: FPZ vs Displacement.

5.3.5CLS

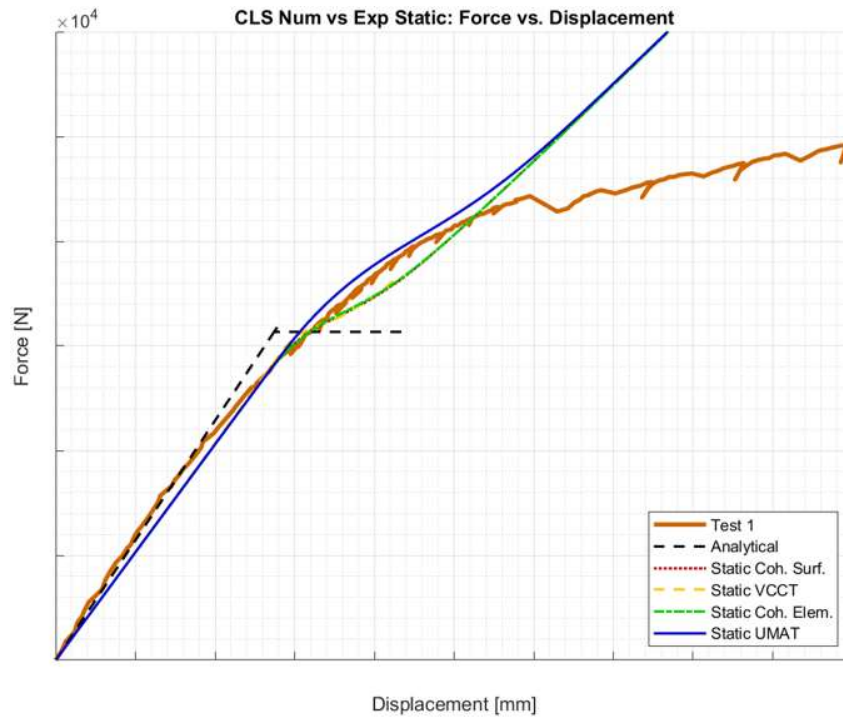
The first comparison that will be presented is the mix mode ratio, that was previously presented to attain the B-K parameter. In Graph 56 the UMAT results is now presented alongside the VCCT. The initial behaviour for the UMAT presents a bigger Mode II ratio, and since VCCT model aborts earlier due to computational issues, the UMAT logs the ratio until the complete crack propagation. Otherwise, the plots are similar, which proves the viability of the UMAT, and that the longer the CLS test extends, the closer to a pure Mode II behaviour it becomes.



Graph 56 – CLS numerical results: Ratio G_{II}/G_T vs Crack Length.

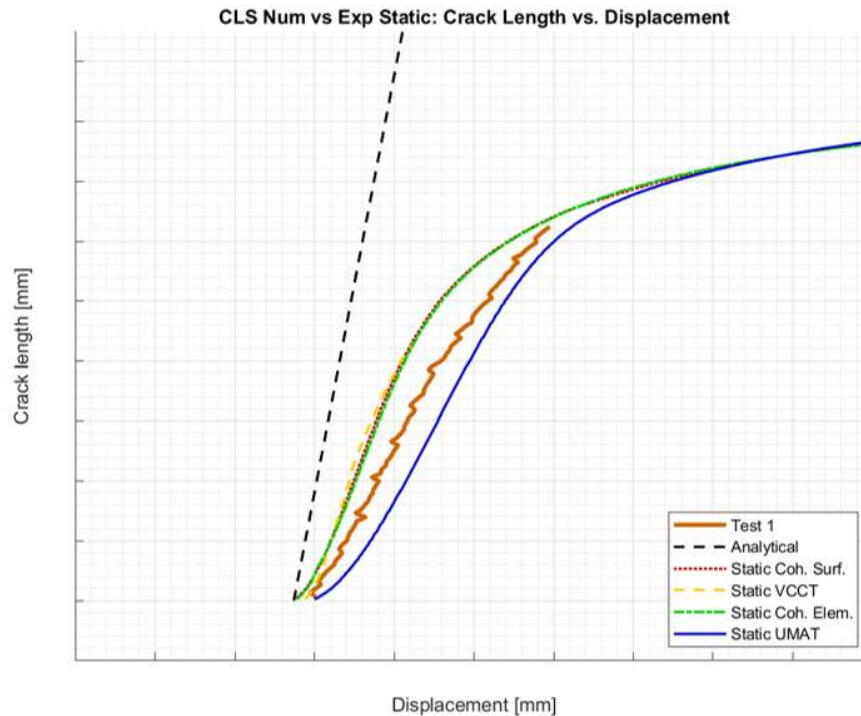
Comparing the Load vs Displacement experimental and numerical results, Graph 57, that don't use the UMAT, there is a reduced force during the crack propagation, due to a lower mix mode ratio for the initial crack propagation. The UMAT has a similar curve to the

experimental test, which further justifies the use of the UMAT for this material. The analytical model could only predict the force and displacement where the crack propagation starts.



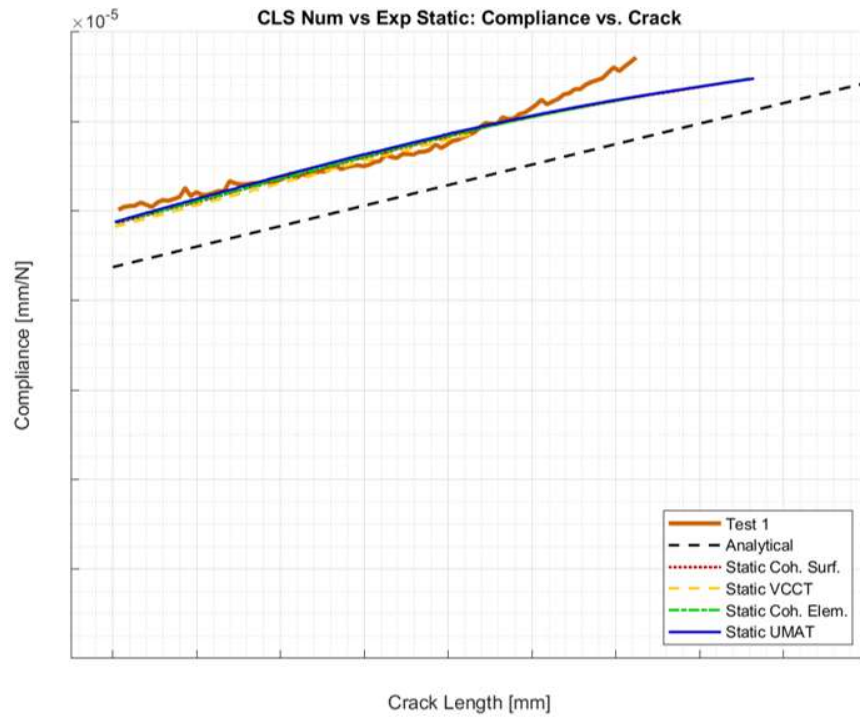
Graph 57 – CLS numerical, experimental, and analytical results: Load vs Displacement.

The next plot, Graph 58, shows the Crack Length vs Displacement, where the slope of the UMAT is closer to the experimental result than the other numerical models.



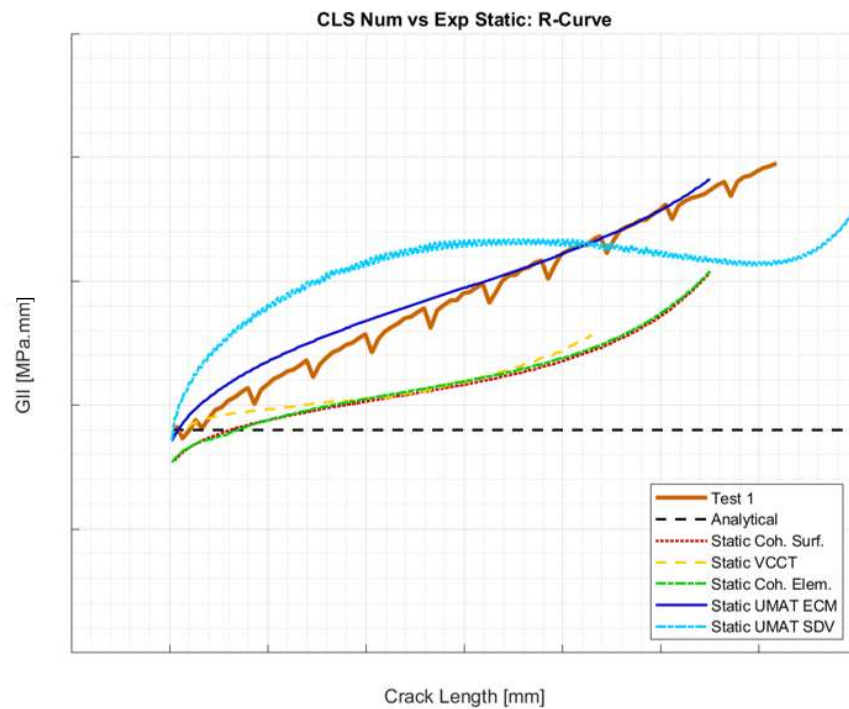
Graph 58 – CLS numerical, experimental, and analytical results: Crack Length vs Displacement.

As for the Compliance vs Crack Length, Graph 59, all the numerical models have a similar plot, which is also alike the experimental curve.



Graph 59 – CLS numerical, experimental, and analytical results: Compliance vs Crack Length.

The previous graph is to attain the slope, to obtain the R-Curve through the ECM, which results in Graph 60.

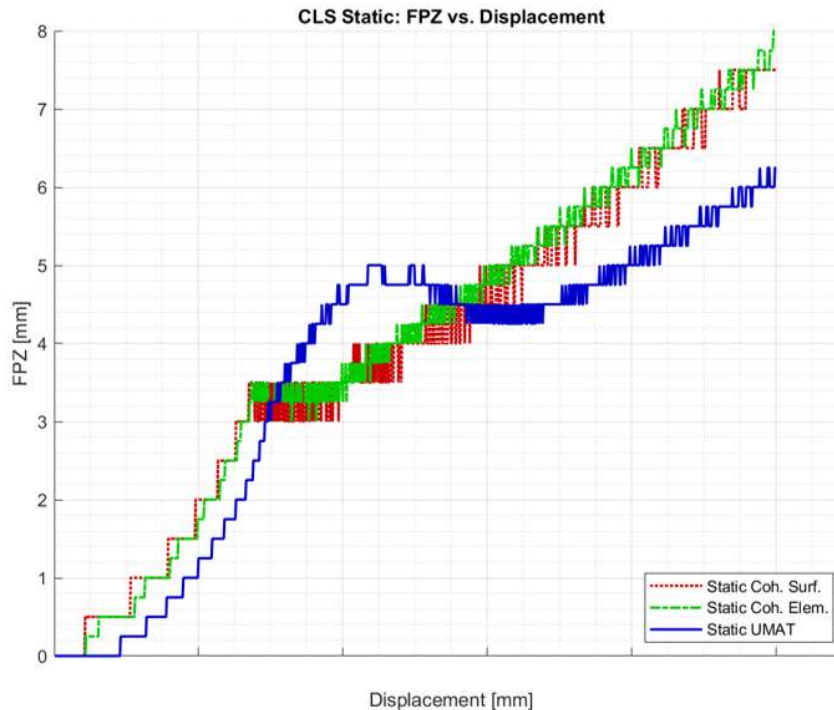


Graph 60 – CLS numerical, experimental, and analytical results: R-Curve

The non-UMAT models underestimate the DFT during the crack propagation for the CLS test. The two UMAT R-curve results are closer to the experimental findings. The different results between the two methods could be caused by the small assumptions of the ECM method uses, for example, where the linear crack plot stops. The SDV method doesn't use any of these assumptions, so it can be a useful to straightforwardly attain a typical shaped R-Curve, even though it wasn't as accurate as the UMAT with ECM at predicting the experimental R-Curve, which followed basically the exact same shape.

The higher DFT in the UMAT compared to the other models during propagation should create a higher FPZ than expected. Graph 61 supports this assessment, where the UMAT shows a higher FPZ during initial propagation.

However, when the CLS specimen starts to behave more as a tensile specimen, this is, where the crack propagation starts to slow down at 60% of the displacement (that corresponds to a 90 mm crack length), the Mode II starts to be more prominent, as Graph 56 displays, creating an increase in the total DFT, which agrees with Graph 60. This increase in DFT correlates to an increase in FPZ, but the UMAT diminishes this effect with increasing Mode II behaviour, making the curve of the UMAT in Graph 61 go below the other numerical models after the linear crack propagation occurs.



Graph 61 – CLS numerical results: FPZ vs Displacement.

5.3.6 ELS

The numerical results for the ELS specimen are shown in Graph 62, Graph 63, Graph 64, Graph 65, and Graph 66 in Annex C with the same plots and reaching analogous conclusions as the prior specimens. The mix mode ratio graph is not present, but it was confirmed the pure Mode II behaviour of this specimen.

6 Conclusions

Although this thesis started with the objective of understanding the delamination behaviour in Mode II of the 3D woven angle warp interlock provided, due to lack of time, only the static behaviour was reached. The other objective was predicting this behaviour with a numerical model. The models employed were: Virtual Crack Closure Technique (VCCT), Cohesive Zone Model (CZM, using both cohesive surfaces and cohesive elements).

The numerical delamination behaviour can be defined as cohesive properties. These properties were attained using various test specimens:

- Thick Adherend Shear Test (TAST) was used to determine the interlaminar shear strength. Additionally, they were used to confirm the elastic shear modulus.
- Four-point End Notched Flexure (4ENF) test was used to attain the Mode II delamination fracture toughness.
- Cracked Lap Shear (CLS) test was used as a mixed mode I+II test, which in combination with the 4ENF, the B-K law parameter was reached.

The TAST specimen was used in the warp and weft directions, resulting in the normalised value of 1 and 0.6 MPa interlaminar shear strength, respectively of each direction. The crack planes were observed, and the main failure mode observed was debonding of fiber-matrix interface. The numerical results were able to accurately predict the failure load and the shear modulus. It was observed that the fracture toughness did not have a great impact on the predicted maximum failure load, only differ the displacement of separation of the arms of the specimen.

The 4ENF test results showed the expected plateau on the Load vs Displacement curve, which defined the region of crack propagation. Using a crack gauge to measure the crack length, and Digital Image Correlation (DIC) analysis for an accurate measurement of the displacement, the Experimental Compliance Method (ECM) was used to attain the Resistance-Curve (R-Curve) of the Mode II delamination fracture toughness, which was found to be a very large value. For comparison, the normalised value of the DFT was 1 MPa · mm. This curve was accurately predicted using every numerical model used. This high value is predicted to occur due to the weaving of the fibers in a three-dimensional setting, leading to extra dissipated energy required to break the fibers. Further analysis of the failure modes of the specimens is required to reach a conclusion of the high DFT value.

Finally, the CLS test results found a normalised DFT value of 0.164 MPa · mm for the initial mixed mode ratio of 71.4% of Mode II delamination. This led to a B-K parameter of 8.3, corresponding to a very abrupt increase in DFT with the increase in Mode II of the specimen.

The numerical models within ABAQUS were not able to accurately predict neither the Load vs Displacement result nor the R-Curve. The CLS specimen increased the mixed mode ratio during propagation, which led to an increase in the Cohesive Zone Length (CZL), the

numerical representation of the Fracture Process Zone (FPZ). The CZL is increased when high values of Energy Released Rate (ERR) are present, such as the value for the DFT of Mode II found.

This large CZL can misrepresent the stress state of the crack tip, resulting in a poor simulation. To reduce the CZL, a new cohesive User Material (UMAT) was designed, where Mode I was represented with a triangle, and Mode II was represented as a trapeze. This means the displacement at failure of a cohesive element in Mode II is greatly decreased, resulting in a lower CZL.

With this UMAT, an accurate prediction of the CLS experimental results for both the Load vs Displacement and R-Curve was achieved.

The strain rate effects were also studied; however, no experimental results were obtained. Nevertheless, the UMAT was prepared for the implementation of these effects, for when the planned experimental tests are performed.

The expectation is that the rate-effects in the FPZ can interact with the well-known rate-dependency of polymers, leading to a very complicated phenomenon, where the failure modes change with rate. This phenomenon can increase in complexity with the very anisotropic material that was studied.

Annex A. CATIA Drawings of the Specimens

This annex saves the part drawings of each specimen designed by the author. The shorter 4ENF is not present due to being previously cut out. These drawings were used to cut and prepare the specimens for the experimental testing.

A.1. TAST Specimen

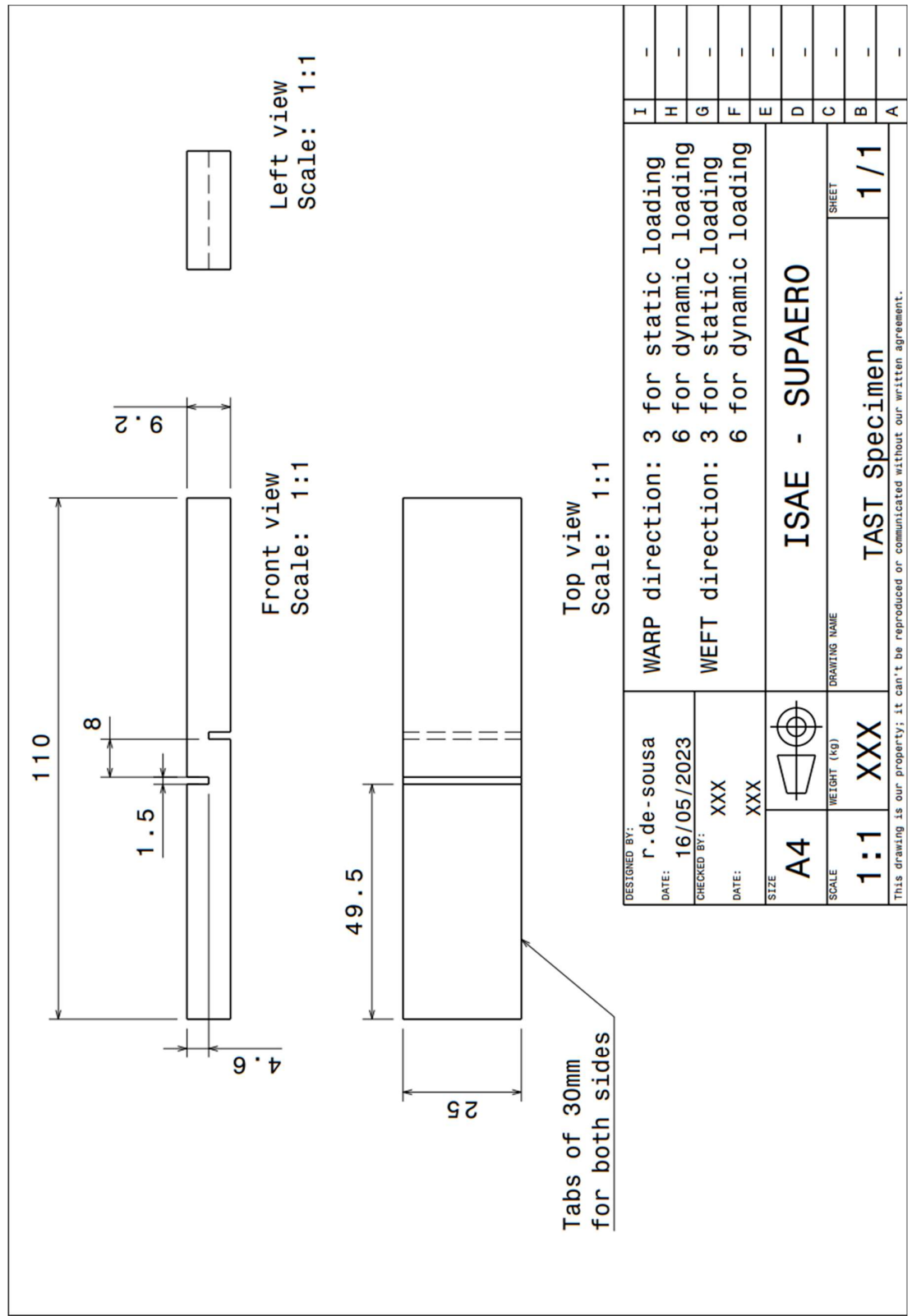


Figure 47 – TAST part drawing from CATIA.

A.2.Long 4ENF Specimen

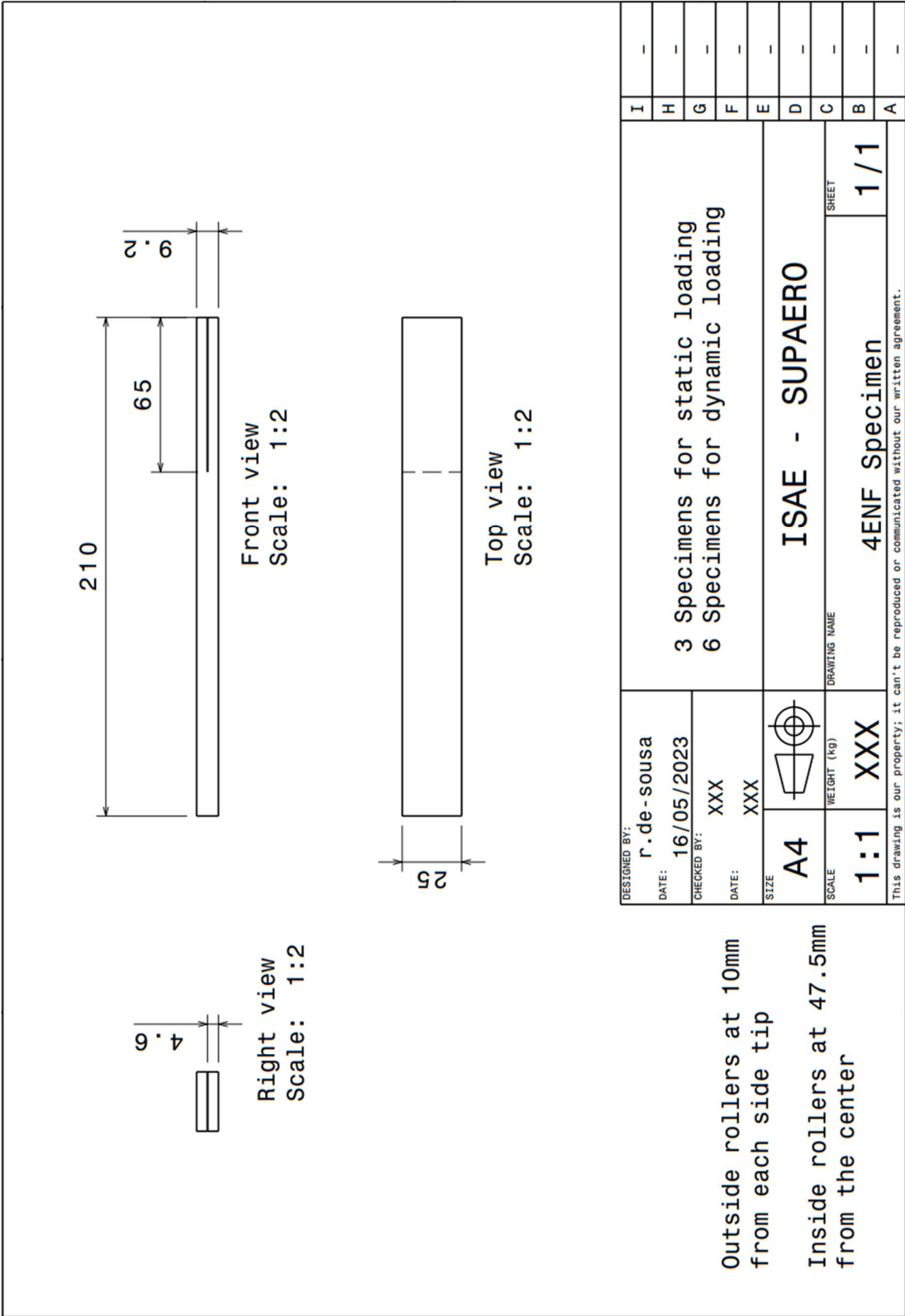


Figure 48 – Long 4ENF part drawing from CATIA.

A.3.CLS Specimen

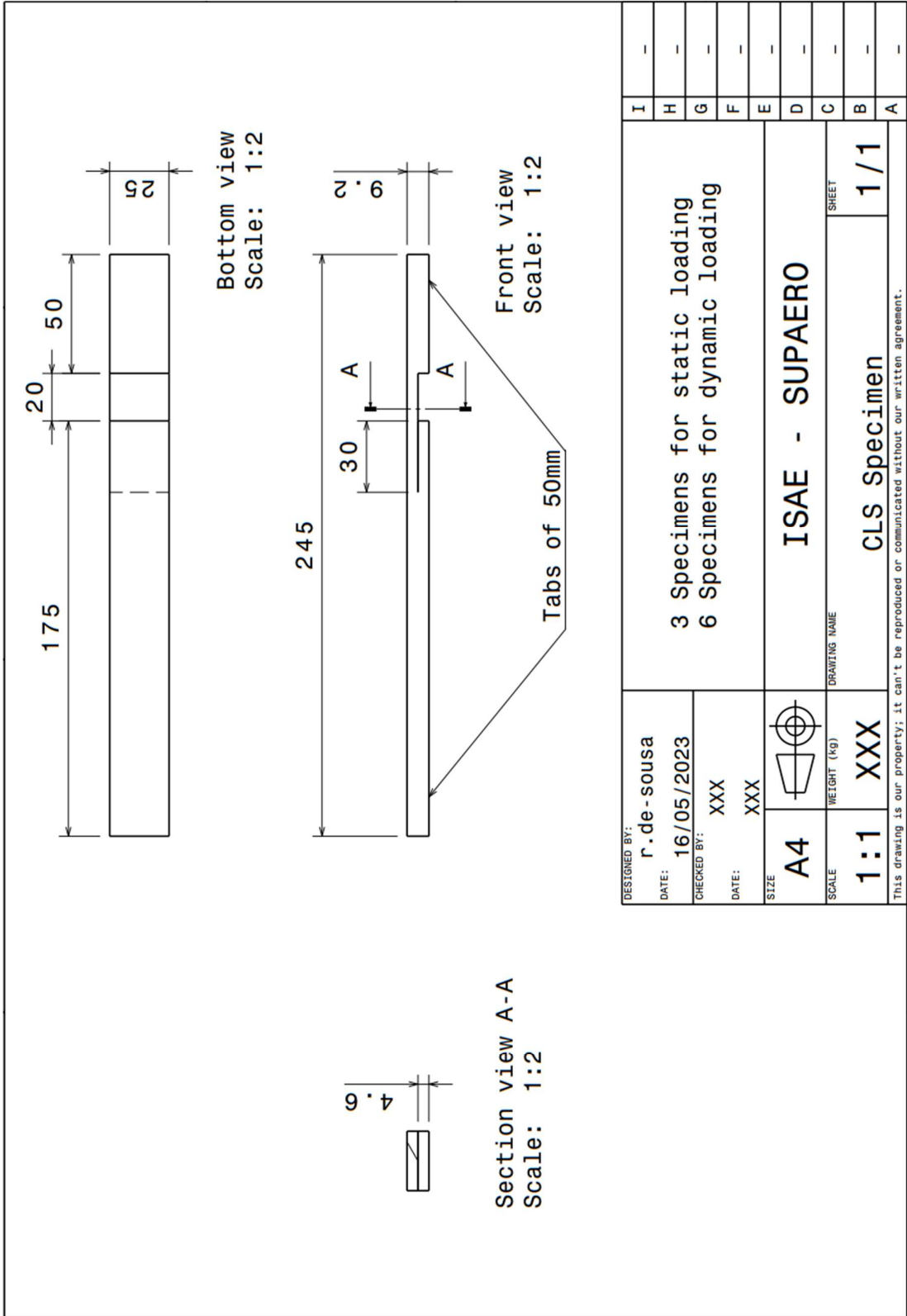


Figure 49 – CLS part drawing from CATIA.

A.4.ELS Specimen

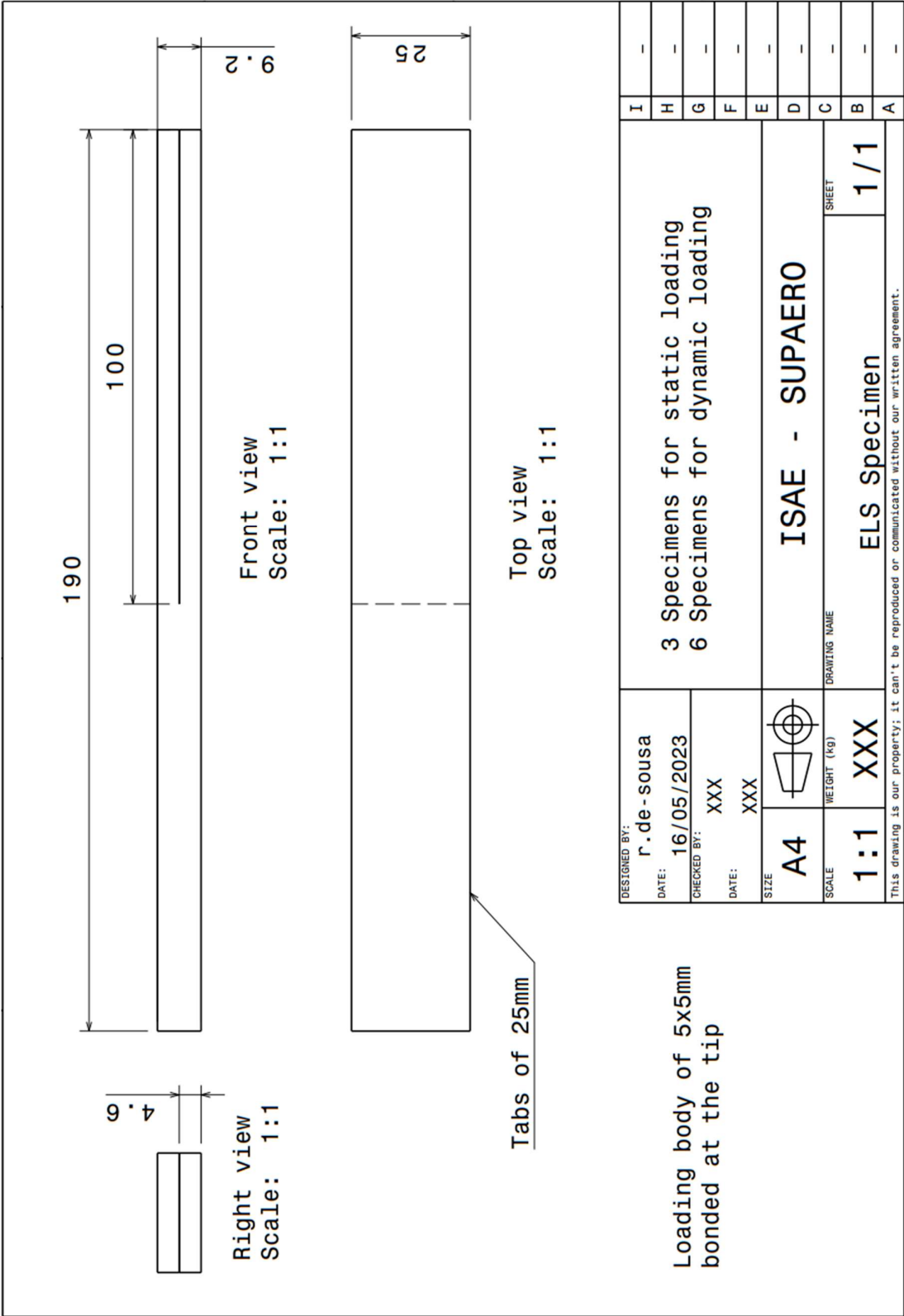


Figure 50 – ELS part drawing from CATIA

Annex B. Python and MATLAB Examples

This annex has some examples of codes that were used during this thesis. Python codes were utilised to create the models for each specimen. Then a different Python code was used for each model of each specimen that recorded all the necessary data from the ODB for analysis, for example, the crack length during propagation. That data was then manipulated to create the results plots with a MATLAB code. Since the Python codes are all relatively similar, only one model of a DFT test will be reported, the UMAT mode of the 4ENF test. The MATLAB codes created were used for both experimental and numerical results, and both use the Experimental Compliance Method, but the experimental results also include the 95% confidence area, hence the 4ENF experimental MATLAB code is the one shown.

Moreover, the ODB reader and the MATLAB codes of the TAST's numerical model without damage will also be displayed since they have a different procedure.

During the internship, an older version of Microsoft Office and MATLAB were used, meaning some adjustments were necessary to be able to operate these versions.

B.1.4ENF UMAT Model Creation

```
#####
####          Rui Jorge de Sousa Goncalves          #####
####          March-July 2023 - Internship at ISAE   #####
####          4ENF Code                             #####
####          ATTENTION: Necessary to check scratch #####
####          directory on each Job                  #####
#####

from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *

##### Dimensions #####

length_L=95.0
roller_pos=10.0    # distance from the BOTTOM roller position to the tip of
the specimen
f_length=2.0*length_L+roller_pos*2.0    # 2L+10*2 for each side = distance
between bottom rollers
p_thick=5.0        # part thickness
coh_thick=0.01
crack_length=65.0  #a+10-> a=55
```

```

crack_tip=f_length-crack_length # position of the crack tip
roller_dist_top=95.0
roller_dist_bot_top_left=47.5
roller_radius=5
roller_mass=1e-05
roller_damping=0.1
roller_rot_inertia=1e-11

```

```

##### Material Composite ##### for 20C

```

```

E1= xxxxx
E2= xxxxx
E3= xxxxx
G12= xxxxx
G13= xxxxx
G23= xxxxx
nu12= xxxxx
nu13= xxxxx
nu23= xxxxx
density= xxxxx

```

```

##### Material Cohesive #####

```

```

K1=1000000
K2=1000000
K3=1000000
sigma1_coh= xxxxx
sigma2_coh= xxxxx
sigma3_coh= xxxxx
GI= xxxxx
GII= xxxxx
GIII= xxxxx
Power_BK=8.3
visco_stab_mat=0.0001
visco_stab_surf=0.0001
visco_stab_elem=1e-8
Section_thickness=1

```

```

##### Mesh #####

```

```

n_coh_elem=int(4*crack_tip)
n_thick_elem=8
spec_mesh_size=0.5

```

```

##### Outputs #####

```

```

n_intervals = 1000 #min=4*crack_tip=f_length-crack_length

```

```

##### Step Standard #####

```

```

step_time=7.5
init_inc = step_time/n_intervals
max_inc = step_time/n_intervals
time_explicit=0.075

```

```

##### Interactions #####

```

```

friction=0.15

```

```

vcct_tolerance=0.05

##### MODEL STATIC UMAT #####

mdb.Model(modelType=STANDARD_EXPLICIT, name='Model-Static-UMAT')

#### Part-Specimen ####

mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='__profile__',
sheetSize=300.0)
mdb.models['Model-Static-UMAT'].sketches['__profile__'].rectangle(point1=(0.0, 0.0),
point2=(f_length, p_thick))
mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='Sketch-Spec',
objectToCopy=
    mdb.models['Model-Static-UMAT'].sketches['__profile__'])
mdb.models['Model-Static-UMAT'].Part(dimensionality=TWO_D_PLANAR, name='Part-
Spec', type=
    DEFORMABLE_BODY)
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].BaseShell(sketch=
    mdb.models['Model-Static-UMAT'].sketches['__profile__'])
del mdb.models['Model-Static-UMAT'].sketches['__profile__']
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(offset=crack_tip
    , principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].PartitionFaceByDatumPlane(datumPlane=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[2], faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask((
    '#1 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(offset=roller_pos-5.0,
    principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(offset=roller_pos+5.0
    , principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(offset=
    f_length-roller_pos-5.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(offset=
    f_length-roller_pos+5.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].PartitionFaceByDatumPlane(datumPlane=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[4], faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask((
    '#1 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].PartitionFaceByDatumPlane(datumPlane=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[5], faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask((
    '#2 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].PartitionFaceByDatumPlane(datumPlane=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[6], faces=

```

```

mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask((
    ['#8 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].PartitionFaceByDatumPlane(datumPlane=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[7], faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask((
    ['#10 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(
    offset=f_length/2.0-length_L/2.0-10.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(
    offset=f_length/2.0-length_L/2.0+10.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(
    offset=f_length/2.0+length_L/2.0+10.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].DatumPlaneByPrincipalPlane(
    offset=f_length/2.0+length_L/2.0-10.0, principalPlane=YZPLANE)
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].Set(faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#3f ]', ), ), name='Spec-Whole')
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].PartitionFaceByDatumPlane(
    datumPlane=mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[13],
    faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#10 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].PartitionFaceByDatumPlane(
    datumPlane=mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[12],
    faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#1 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].PartitionFaceByDatumPlane(
    datumPlane=mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[14],
    faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#8 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].Set(faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#3ff ]', ), ), name='Spec-Whole')
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].PartitionFaceByDatumPlane(
    datumPlane=mdb.models['Model-Static-UMAT'].parts['Part-Spec'].datums[15],
    faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
    ( ['#80 ]', ), ))

#### Part-Cohesive ####

mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='__profile__',
    sheetSize=300.0)

```

```

mdb.models['Model-Static-UMAT'].sketches['__profile__'].rectangle(point1=(
    0.0, p_thick), point2=(crack_tip, p_thick+coh_thick))
mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='Sketch-Coh',
    objectToCopy=mdb.models['Model-Static-UMAT'].sketches['__profile__'])
mdb.models['Model-Static-UMAT'].Part(dimensionality=TWO_D_PLANAR, name=
    'Part-Coh', type=DEFORMABLE_BODY)
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].BaseShell(sketch=
    mdb.models['Model-Static-UMAT'].sketches['__profile__'])
del mdb.models['Model-Static-UMAT'].sketches['__profile__']
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].Set(faces=
    mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].faces.getSequenceFromMask(
    ('[#1 ]', ), ), name='CohZone-Whole')
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].Surface(name='Surf-Coh-Top'
    , sideEdges=
    mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].edges.getSequenceFromMask(
    ('[#4 ]', ), ))
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].Surface(name='Surf-Coh-Bot'
    , sideEdges=
    mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].edges.getSequenceFromMask(
    ('[#1 ]', ), ))

##### Part-Rollers #####

mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='__profile__',
    sheetSize=300.0)
mdb.models['Model-Static-
UMAT'].sketches['__profile__'].CircleByCenterPerimeter(
    center=(0.0, 0.0), point1=(roller_radius, 0.0))
mdb.models['Model-Static-UMAT'].ConstrainedSketch(name='Sketch-Roller',
    objectToCopy=mdb.models['Model-Static-UMAT'].sketches['__profile__'])
mdb.models['Model-Static-UMAT'].Part(dimensionality=TWO_D_PLANAR, name=
    'Part-Roller', type=DISCRETE_RIGID_SURFACE)
mdb.models['Model-Static-UMAT'].parts['Part-Roller'].BaseWire(sketch=
    mdb.models['Model-Static-UMAT'].sketches['__profile__'])
del mdb.models['Model-Static-UMAT'].sketches['__profile__']
mdb.models['Model-Static-UMAT'].parts['Part-Roller'].ReferencePoint(point=
    mdb.models['Model-Static-UMAT'].parts['Part-Roller'].InterestingPoint(
    mdb.models['Model-Static-UMAT'].parts['Part-Roller'].edges[0], CENTER))
mdb.models['Model-Static-UMAT'].parts['Part-Roller'].Set(name=
    'Set-RP-Rollers', referencePoints=(
    mdb.models['Model-Static-UMAT'].parts['Part-Roller'].referencePoints[2],
    ))
mdb.models['Model-Static-UMAT'].parts['Part-
Roller'].engineeringFeatures.PointMassInertia(
    alpha=roller_damping, composite=0.0, mass=roller_mass, name='Inertia-
Roller', region=
    mdb.models['Model-Static-UMAT'].parts['Part-Roller'].sets['Set-RP-
Rollers'])
mdb.models['Model-Static-UMAT'].parts['Part-
Roller'].engineeringFeatures.inertias['Inertia-Roller'].setValues(
    i11=roller_rot_inertia, i22=roller_rot_inertia, i33=roller_rot_inertia)

##### Material Properties #####

mdb.models['Model-Static-UMAT'].Material(name='Material-Composite')

```

```

mdb.models['Model-Static-UMAT'].materials['Material-Composite'].Density(
    table=((density, ), ), )
mdb.models['Model-Static-UMAT'].materials['Material-Composite'].Elastic(
    table=(E1, E2, E3, nu12, nu13, nu23, G12, G13,
    G23), ), type=ENGINEERING_CONSTANTS)

mdb.models['Model-Static-UMAT'].Material(name='Material-Cohesive')
mdb.models['Model-Static-UMAT'].materials['Material-Cohesive'].Density(table=
    ((density, ), ))
mdb.models['Model-Static-UMAT'].Material(name='Material-Cohesive')
mdb.models['Model-Static-UMAT'].materials['Material-Cohesive'].Density(table=
    ((density, ), ))
mdb.models['Model-Static-UMAT'].materials['Material-Cohesive'].Depvar(
    n=17)
mdb.models['Model-Static-UMAT'].materials['Material-Cohesive'].UserMaterial(
    mechanicalConstants=(K1/10, K2/10, K3/10, sigma1_coh, sigma2_coh,
    sigma3_coh, GI,
    GII, GIII, Power_BK, 0.001, 0.9999))

##### Sections and assignment and material orientation #####

mdb.models['Model-Static-UMAT'].HomogeneousSolidSection(material=
    'Material-Composite', name='Section-Composite', thickness=1.0)
mdb.models['Model-Static-UMAT'].CohesiveSection(initialThickness=1.0,
    initialThicknessType=SPECIFY, material='Material-Cohesive', name=
    'Section-Cohesive', outOfPlaneThickness=None,
    response=TRACTION_SEPARATION)

mdb.models['Model-Static-UMAT'].parts['Part-Coh'].SectionAssignment(offset=
    0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=
    mdb.models['Model-Static-UMAT'].parts['Part-Coh'].sets['CohZone-Whole'],
    sectionName='Section-Cohesive', thicknessAssignment=FROM_SECTION)
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].SectionAssignment(offset=
    0.0, offsetField='', offsetType=MIDDLE_SURFACE, region=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].sets['Spec-Whole'],
    sectionName='Section-Composite', thicknessAssignment=FROM_SECTION)

mdb.models['Model-Static-UMAT'].parts['Part-Spec'].MaterialOrientation(
    additionalRotationType=ROTATION_NONE, axis=AXIS_3, fieldName='',
    localCsys=
    None, orientationType=GLOBAL, region=
    mdb.models['Model-Static-UMAT'].parts['Part-Spec'].sets['Spec-Whole'],
    stackDirection=STACK_3)

##### Assembly #####

mdb.models['Model-Static-UMAT'].rootAssembly.DatumCsysByDefault(CARTESIAN)
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Spec-1', part=mdb.models['Model-Static-UMAT'].parts['Part-Spec'])
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Coh-1', part=mdb.models['Model-Static-UMAT'].parts['Part-Coh'])
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Spec-2', part=mdb.models['Model-Static-UMAT'].parts['Part-Spec'])
mdb.models['Model-Static-UMAT'].rootAssembly.translate(instanceList=(
    'Part-Spec-2', ), vector=(0.0, p_thick+coh_thick, 0.0))
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Roller-1', part=
    mdb.models['Model-Static-UMAT'].parts['Part-Roller'])

```

```

mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Roller-2', part=
        mdb.models['Model-Static-UMAT'].parts['Part-Roller'])
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Roller-3', part=
        mdb.models['Model-Static-UMAT'].parts['Part-Roller'])
mdb.models['Model-Static-UMAT'].rootAssembly.Instance(dependent=ON, name=
    'Part-Roller-4', part=
        mdb.models['Model-Static-UMAT'].parts['Part-Roller'])
mdb.models['Model-Static-UMAT'].rootAssembly.translate(instanceList=(
    'Part-Roller-4', ), vector=(roller_pos, -roller_radius, 0.0))
mdb.models['Model-Static-UMAT'].rootAssembly.translate(instanceList=(
    'Part-Roller-3', ), vector=(f_length-roller_pos, -roller_radius, 0.0))
mdb.models['Model-Static-UMAT'].rootAssembly.translate(instanceList=(
    'Part-Roller-2', ), vector=(roller_pos+roller_dist_bot_top_left,
p_thick*2.0+roller_radius+coh_thick, 0.0))
mdb.models['Model-Static-UMAT'].rootAssembly.translate(instanceList=(
    'Part-Roller-1', ),
vector=(roller_pos+roller_dist_bot_top_left+roller_dist_top,
p_thick*2.0+roller_radius+coh_thick, 0.0))

mdb.models['Model-Static-
UMAT'].rootAssembly.ReferencePoint(point=(roller_pos+roller_dist_bot_top_left
+roller_dist_top/2.0,
    p_thick*2.0+roller_radius+coh_thick, 0.0))

mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-LeftBot-Spec'
, side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
1'].edges.getSequenceFromMask(
    ('[#400000 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
    'Surf-LeftBot-Roller', side2Edges=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
4'].edges.getSequenceFromMask(
    ('[#1 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-LeftTop-Spec'
, side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
2'].edges.getSequenceFromMask(
    ('[#2000 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
    'Surf-LeftTop-Roller', side2Edges=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
2'].edges.getSequenceFromMask(
    ('[#1 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
    'Surf-RightTop-Spec', side1Edges=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
2'].edges.getSequenceFromMask(
    ('[#8000022 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
    'Surf-RightTop-Roller', side2Edges=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
1'].edges.getSequenceFromMask(
    ('[#1 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
    'Surf-RightBot-Spec', side1Edges=

```

```

        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
1'].edges.getSequenceFromMask(
    ('[#20000 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name=
'Surf-RightBot-Roller', side2Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
3'].edges.getSequenceFromMask(
    ('[#1 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-Crack-Top',
    side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
2'].edges.getSequenceFromMask(
    ('[#10060080 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-Crack-Bot',
    side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
1'].edges.getSequenceFromMask(
    ('[#40088020 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-Coh-Bot',
    side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
1'].edges.getSequenceFromMask(
    ('[#8902202 ]', ), ))
mdb.models['Model-Static-UMAT'].rootAssembly.Surface(name='Surf-Coh-Top',
    side1Edges=
    mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Spec-
2'].edges.getSequenceFromMask(
    ('[#6401808 ]', ), ))

##### Step and Outputs #####

mdb.models['Model-Static-UMAT'].rootAssembly.regenerate()
mdb.models['Model-Static-UMAT'].StaticStep(adaptiveDampingRatio=0.05,
    continueDampingFactors=False, initialInc=init_inc, maxInc=max_inc,
maxNumInc=
    100000, minInc=1e-20, name='Step-Static-El', nlgeom=ON, previous=
    'Initial', stabilizationMagnitude=0.0002, stabilizationMethod=
    DISSIPATED_ENERGY_FRACTION, timePeriod=step_time)
mdb.models['Model-Static-UMAT'].fieldOutputRequests['F-Output-1'].setValues(
    numIntervals=n_intervals/5, variables=('S', 'PE', 'PEEQ', 'PEMAG', 'LE',
'U', 'RF',
    'CF', 'CSTRESS', 'CDISP', 'SDEG', 'ENRRT', 'EFENRRTR', 'CSDMG', 'SDV'))
mdb.models['Model-Static-UMAT'].rootAssembly.Set(name='Set-RP-Load',
    referencePoints=(mdb.models['Model-Static-
UMAT'].rootAssembly.referencePoints[16], ))
mdb.models['Model-Static-UMAT'].historyOutputRequests['H-Output-
1'].setValues(
    numIntervals=n_intervals, rebar=EXCLUDE, region=
    mdb.models['Model-Static-UMAT'].rootAssembly.sets['Set-RP-Load'],
    sectionPoints=DEFAULT, variables=('UT', 'RT'))
mdb.models['Model-Static-UMAT'].HistoryOutputRequest(createStepName=
    'Step-Static-El', name='H-Output-SDEG', numIntervals=n_intervals,
    rebar=EXCLUDE,
    region=
    mdb.models['Model-Static-UMAT'].rootAssembly.allInstances['Part-Coh-
1'].sets['CohZone-Whole'])

```

```

, sectionPoints=DEFAULT,
variables=('S11', 'S22', 'S33', 'S12', 'S13', 'S23', 'LE11', 'LE22', 'LE33', 'LE12', 'L
E13', 'LE23', 'SDEG', 'SDV'))
mdb.models['Model-Static-UMAT'].historyOutputRequests.changeKey(fromName=
'H-Output-1', toName='H-Output-RP')
mdb.models['Model-Static-UMAT'].steps['Step-Static-E1'].control.setValues(
allowPropagation=OFF, resetDefaultValues=OFF, timeIncrementation=(4.0,
8.0,
9.0, 16.0, 10.0, 4.0, 12.0, 15.0, 6.0, 3.0, 50.0))

##### Mesh Spec, Roller, Cohesive Elements #####

mdb.models['Model-Static-UMAT'].parts['Part-Spec'].setMeshControls(elemShape=
QUAD, regions=
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
(['#3ff'], ), ), technique=STRUCTURED)
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].setElementType(elemTypes=(
ElemType(elemCode=CPE4, elemLibrary=STANDARD), ElemType(elemCode=CPE3,
elemLibrary=STANDARD)), regions=(
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].faces.getSequenceFromMask(
(['#3ff'], ), ), ))

mdb.models['Model-Static-UMAT'].parts['Part-Spec'].seedEdgeBySize(constraint=
FINER, deviationFactor=0.1, edges=
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].edges.getSequenceFromMask(
(['#5edebaaa'], ), ), size=spec_mesh_size/2)
mdb.models['Model-Static-UMAT'].parts['Part-Spec'].seedEdgeByBias(biasMethod=
DOUBLE, constraint=FINER, endEdges=
mdb.models['Model-Static-UMAT'].parts['Part-
Spec'].edges.getSequenceFromMask(
(['#21214555'], ), ), number=n_thick_elem, ratio=4.0)

mdb.models['Model-Static-UMAT'].parts['Part-Spec'].generateMesh()

mdb.models['Model-Static-UMAT'].parts['Part-Roller'].seedEdgeByNumber(
constraint=FINER, edges=
mdb.models['Model-Static-UMAT'].parts['Part-
Roller'].edges.getSequenceFromMask(
(['#1'], ), ), number=roller_radius*30)
mdb.models['Model-Static-UMAT'].parts['Part-Roller'].generateMesh()

mdb.models['Model-Static-UMAT'].parts['Part-Coh'].setMeshControls(elemShape=
QUAD, regions=
mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].faces.getSequenceFromMask(
(['#1'], ), ), technique=SWEEP)
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].setSweepPath(edge=
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].edges[3], region=
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].faces[0], sense=
FORWARD)
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].setElementType(elemTypes=(
ElemType(elemCode=COH2D4, elemLibrary=STANDARD, elemDeletion=OFF,
viscosity=visco_stab_elem), ElemType(
elemCode=UNKNOWN_TRI, elemLibrary=STANDARD)), regions=(

```

```

mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].faces.getSequenceFromMask(
    ('[#1 ]', ), ), )
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].seedEdgeByNumber(
    constraint=FINER, edges=
    mdb.models['Model-Static-UMAT'].parts['Part-
Coh'].edges.getSequenceFromMask(
    ('[#5 ]', ), ), number=n_coh_elem)
mdb.models['Model-Static-UMAT'].parts['Part-Coh'].generateMesh()

##### Interactions and Constrains #####

mdb.models['Model-Static-UMAT'].ContactProperty(
    'IntProp-Contact-Roller-Spec')
mdb.models['Model-Static-UMAT'].interactionProperties['IntProp-Contact-
Roller-Spec'].TangentialBehavior(
    dependencies=0, directionality=ISOTROPIC, elasticSlipStiffness=None,
    formulation=PENALTY, fraction=0.005, maximumElasticSlip=FRACTION,
    pressureDependency=OFF, shearStressLimit=None, slipRateDependency=OFF,
    table=((friction, ), ), temperatureDependency=OFF)
mdb.models['Model-Static-UMAT'].interactionProperties['IntProp-Contact-
Roller-Spec'].NormalBehavior(
    allowSeparation=ON, constraintEnforcementMethod=DEFAULT,
    pressureOverclosure=HARD)
mdb.models['Model-Static-UMAT'].SurfaceToSurfaceContactStd(adjustMethod=None,
    clearanceRegion=None, createStepName='Initial', datumAxis=None,
    initialClearance=OMIT, interactionProperty='IntProp-Contact-Roller-Spec',
    main=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-LeftBot-
Roller']
    , name='Int-LeftBot', secondary=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-LeftBot-
Spec']
    , sliding=FINITE, thickness=ON)
mdb.models['Model-Static-UMAT'].SurfaceToSurfaceContactStd(adjustMethod=None,
    clearanceRegion=None, createStepName='Initial', datumAxis=None,
    initialClearance=OMIT, interactionProperty='IntProp-Contact-Roller-Spec',
    main=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-LeftTop-
Roller']
    , name='Int-LeftTop', secondary=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-LeftTop-
Spec']
    , sliding=FINITE, thickness=ON)
mdb.models['Model-Static-UMAT'].SurfaceToSurfaceContactStd(adjustMethod=None,
    clearanceRegion=None, createStepName='Initial', datumAxis=None,
    initialClearance=OMIT, interactionProperty='IntProp-Contact-Roller-Spec',
    main=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-RightBot-
Roller']
    , name='Int-RightBot', secondary=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-RightBot-
Spec']
    , sliding=FINITE, thickness=ON)
mdb.models['Model-Static-UMAT'].SurfaceToSurfaceContactStd(adjustMethod=None,
    clearanceRegion=None, createStepName='Initial', datumAxis=None,
    initialClearance=OMIT, interactionProperty='IntProp-Contact-Roller-Spec',
    main=

```

```

mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-RightTop-
Roller']
    , name='Int-RightTop', secondary=
mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-RightTop-
Spec']
    , sliding=FINITE, thickness=ON)
mdb.models['Model-Static-UMAT'].ContactProperty('IntProp-Contact-Crack')
mdb.models['Model-Static-UMAT'].interactionProperties['IntProp-Contact-
Crack'].TangentialBehavior(
    formulation=FRICTIONLESS)
mdb.models['Model-Static-UMAT'].interactionProperties['IntProp-Contact-
Crack'].NormalBehavior(
    allowSeparation=ON, constraintEnforcementMethod=DEFAULT,
    pressureOverclosure=HARD)
mdb.models['Model-Static-UMAT'].SurfaceToSurfaceContactStd(adjustMethod=NONE,
    clearanceRegion=None, createStepName='Initial', datumAxis=None,
    initialClearance=OMIT, interactionProperty='IntProp-Contact-Crack',
    main=
        mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-Crack-Bot'],
        name='Int-Crack', secondary=
            mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-Crack-Top'],
            sliding=FINITE, thickness=ON)

mdb.models['Model-Static-UMAT'].Tie(adjust=ON, main=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-Coh-Top'],
    name='Tie-CohTop', positionToleranceMethod=COMPUTED, secondary=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Coh-
1'].surfaces['Surf-Coh-Top']
    , thickness=ON, tieRotations=ON)
mdb.models['Model-Static-UMAT'].Tie(adjust=ON, main=
    mdb.models['Model-Static-UMAT'].rootAssembly-surfaces['Surf-Coh-Bot'],
    name='Tie-CohBot', positionToleranceMethod=COMPUTED, secondary=
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Coh-
1'].surfaces['Surf-Coh-Bot']
    , thickness=ON, tieRotations=ON)
mdb.models['Model-Static-UMAT'].Coupling(controlPoint=
    mdb.models['Model-Static-UMAT'].rootAssembly.sets['Set-RP-Load'],
    couplingType=KINEMATIC, influenceRadius=WHOLE_SURFACE, localCsys=None,
    name='RP-Coupling', surface=Region(referencePoints=(
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
1'].referencePoints[2],
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
2'].referencePoints[2],
    )), u1=ON, u2=ON, ur3=ON)

##### Loads #####

mdb.models['Model-Static-UMAT'].rootAssembly.Set(name='Set-Encastre',
    referencePoints=((
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
4'].referencePoints[2],
    ), (
        mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
3'].referencePoints[2],
    )))
mdb.models['Model-Static-UMAT'].EncastreBC(createStepName='Initial',
    localCsys=None, name='BC-Encastre', region=
    mdb.models['Model-Static-UMAT'].rootAssembly.sets['Set-Encastre'])

```

```

mdb.models['Model-Static-UMAT'].rootAssembly.Set(name='Set-Rollers-Top',
referencePoints=((
mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
2'].referencePoints[2],
), (
mdb.models['Model-Static-UMAT'].rootAssembly.instances['Part-Roller-
1'].referencePoints[2],
)))
mdb.models['Model-Static-UMAT'].DisplacementBC(amplitude=UNSET,
createStepName='Step-Static-E1', distributionType=UNIFORM, fieldName='',
fixed=OFF, localCsys=None, name='BC-Load-Disp', region=
mdb.models['Model-Static-UMAT'].rootAssembly.sets['Set-RP-Load'], u1=
0, u2=-step_time, ur3=UNSET)

##### Job #####

mdb.models['Model-Static-UMAT'].rootAssembly.regenerate()
mdb.Job(atTime=None, contactPrint=OFF, description='', echoPrint=OFF,
explicitPrecision=SINGLE, getMemoryFromAnalysis=True, historyPrint=OFF,
memory=90, memoryUnits=PERCENTAGE, model='Model-Static-UMAT', modelPrint=
OFF, multiprocessingMode=DEFAULT, name='Job-Static-UMAT',
nodalOutputPrecision=SINGLE, numCpus=1, numGPUs=0,
numThreadsPerMpiProcess=
1, queue=None, resultsFormat=ODB, scratch='D:\\temp_abaqus',
type=ANALYSIS,
userSubroutine='C:\\Users\\r.de-
sousa\\Desktop\\Modelation\\Rui\\UMAT\\umat_rui_trapeze.f', waitHours=0,
waitMinutes=0)

mdb.models['Model-Static-UMAT'].steps['Step-Static-E1'].setValues(
initialInc=init_inc*1e-05, maxInc=max_inc*1e-05,
timePeriod=step_time*1e-5)

##### Job #####

mdb.models['Model-Static-UMAT'].rootAssembly.regenerate()
mdb.Job(atTime=None, contactPrint=OFF, description='', echoPrint=OFF,
explicitPrecision=SINGLE, getMemoryFromAnalysis=True, historyPrint=OFF,
memory=90, memoryUnits=PERCENTAGE, model='Model-Static-UMAT', modelPrint=
OFF, multiprocessingMode=DEFAULT, name='Job-Dynamic-UMAT',
nodalOutputPrecision=SINGLE, numCpus=1, numGPUs=0,
numThreadsPerMpiProcess=
1, queue=None, resultsFormat=ODB, scratch='D:\\temp_abaqus',
type=ANALYSIS,
userSubroutine='C:\\Users\\r.de-
sousa\\Desktop\\Modelation\\Rui\\UMAT\\umat_rui_trapeze.f', waitHours=0,
waitMinutes=0)
mdb.models['Model-Static-UMAT'].rootAssembly.regenerate()
mdb.jobs['Job-Static-UMAT'].submit(consistencyChecking=OFF)
mdb.jobs['Job-Static-UMAT'].waitForCompletion()

```

B.2.4ENF UMAT ODB Reader

```
#####
##      Example  Reading the ODB file      ##
#####
# Rui Goncalves 31-03-2023 #####
# To use in Post / Results #####
# Click File, choose Run Script in the menu ####
# import module for ABAQUS
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *

import random
from array import *
from odbAccess import openOdb
import odbAccess

# import module Python

import math, numpy, time, os, shutil
from numpy import zeros, array
import csv

#=====
Nb_element = 580#n_coh_elem      # Set number of cohesive element
L_crack     = 145.0/Nb_element#crack_tip/Nb_element # Equal to the element
length
D_max       = 0.9999           # Max damage value
D_min       = 0.0001           # Min damage value
b           = 25
crack       = 55.0#crack_size
name='Static-El'
#=====
odbname='/Job-Static-UMAT'      # Name of the ODB file
# PATH
path = os.getcwd()

myodbpath = path+odbname+'.odb'
odb = openOdb(myodbpath)

# Type of Date to be save

# Example here save Load-time and displacement-time on the RP1 point declare
in the assembly
step1 = odb.steps['Step-'+name]
region_node = step1.historyRegions['Node ASSEMBLY.1']
```

```

F2Data = region_node.historyOutputs['RF2'].data
u2Data = region_node.historyOutputs['U2'].data

# Save the SDEG values in a dictionary for each element
FailDataCache = {}
CoefData = {}
SRData = {}
GData = {}
for j in range(1, Nb_element+1):
    region_element = step1.historyRegions['Element PART-COH-1.'+str(j)+' Int
Point 1']
    FailDataCache[j] = region_element.historyOutputs['SDV2'].data
    CoefData[j] = region_element.historyOutputs['SDV7'].data
    SRData[j] = region_element.historyOutputs['SDV4'].data
    GData[j] = region_element.historyOutputs['SDV5'].data

# Write the csv file with every data
with open('ODB-'+name+'-UMAT-combined.csv', 'wb') as file_results:
    writer = csv.writer(file_results, delimiter=';')
    writer.writerow(['time', 'disp', 'force', 'FPZ', 'time_dmg', 'crack',
'element', 'GII/GT', 'Strain-Rate', 'Gc'])

    # Save displacement u2 and force F2
    for i in range(1, len(u2Data)):
        time1, u2 = u2Data[i]
        time, F2 = F2Data[i]
        FPZ=0.0 # Restart the FPZ calculation
        # Save FPZ length for each time
        for n in range(1, Nb_element+1):
            time, dmg = FailDataCache[n][i-1]
            if D_min<dmg<D_max:
                FPZ += L_crack
        j=Nb_element-i+1

    if j>0:
        # Save crack data
        for (time_dmg, dmg), (time_dmg, ratio), (time_dmg, SR),
(time_dmg, Gc) in zip(FailDataCache[j], CoefData[j], SRData[j], GData[j]):
            if dmg >= D_max:
                crack += L_crack
                writer.writerow(['%10.6E' % (time1/1000000), '%10.6E' % (-
u2/1000000), '%10.6E' % (-F2*b/1000000), '%10.6E' % (FPZ/1000000), '%10.6E' %
(time_dmg/1000000), '%10.6E' % (crack/1000000), '%d' % j, '%10.6E' %
(ratio/1000000), '%10.6E' % (SR/1000000), '%10.6E' % (Gc/1000000)])
                break
            if time_dmg >= 7.4999 and dmg<D_max:
                writer.writerow(['%10.6E' % (time1/1000000), '%10.6E' % (-
u2/1000000), '%10.6E' % (-F2*b/1000000), '%10.6E' % (FPZ/1000000)])
                break
        else:
            writer.writerow(['%10.6E' % (time1/1000000), '%10.6E' % (-
u2/1000000), '%10.6E' % (-F2*b/1000000), '%10.6E' % (FPZ/1000000)])
# END OF FILE
#=====

```

B.3.Experimental 4ENF MATLAB

Here a main code exists, which will be the first reported, followed by the subcode that produces the analytical curves.

```
clear
clc
close all

min_crack=50;
polyfit_degree=1;
polyfit_degree_95_F_disp=6;
polyfit_degree_95_a_disp=2;
polyfit_degree_95_C_a=1;
polyfit_degree_95_R_curve=3;

figPos = [100 100 780 585];
b=25;
%% Experimental reader
experimental_file{1}=('4.1ENF4 Long Data for COMPARISON.xlsx');
experimental_file{2}=('4.2ENF4 Long Data for COMPARISON.xlsx');
experimental_file{3}=('4.3ENF4 Long Data for COMPARISON.xlsx');
for i=1:length(experimental_file)
    data=readtable(experimental_file{i});
    time=data(:,1);
    nan_rows=any(isnan(time{:,:}),2);
    time(nan_rows,:)=[];
    disp=data(:,2);
    nan_rows=any(isnan(disp{:,:}),2);
    disp(nan_rows,:)=[];
    force=data(:,3);
    nan_rows=any(isnan(force{:,:}),2);
    force(nan_rows,:)=[];
    crack=data(:,4);
    nan_rows=any(isnan(crack{:,:}),2);
    crack(nan_rows,:)=[];
    if i==1
        machine_corr_disp=data(:,6);
        nan_rows=any(isnan(machine_corr_disp{:,:}),2);
        machine_corr_disp(nan_rows,:)=[];
        raw_disp=data(:,5);
        force_raw=data(:,7);
        figure(5)
        set(figure(5), 'Position', figPos);
        hold on
        plot(raw_disp{:,:},force_raw{:,:},'LineWidth',1.5)
        plot(machine_corr_disp{:,:}, force{:,:},'LineWidth',1.5);
        plot(disp{:,:}, force{:,:},'LineWidth',1.5);
        xlim([0 10]);
        ylim([0 6000]);
        grid on
        grid minor
        xlabel('Displacement [mm]');
        ylabel('Force [N]');
        title('ENF4 Test 1 Static: Local vs. Global Displacement (vs. Force)');
        legend({'Machine Disp Raw','Machine Disp Corrected (Global)','DIC Disp (Local)'},'Location','southeast')
```

```

        print(ffigure(5),'88ENF4 Test 1 Static Local vs Global Displacement (vs
Force) now only local','-dpng');
        close(5)
    end

    %% Plot of displacement and force

    figure(1)
    set(figure(1), 'Position', figPos);
    hold on
    if i==1 || i==4
        plot(displacement, force(:,i),'Color',[0.8 0 0],'LineWidth',1.5);
    elseif i==2 || i==5
        plot(displacement, force(:,i),'Color',[0 0.8 0],'LineWidth',1.5);
    elseif i==3 || i==6
        plot(displacement, force(:,i),'Color',[0 0 0.8],'LineWidth',1.5);
    end
    grid on
    grid minor
    xlabel('Displacement [mm]');
    ylabel('Force [N]');
    if i==3
        title('ENF4 Test 1,2,3 Static: Force vs. Displacement');
        legend({'Test 1','Test 2','Test 3'},'Location','southeast');
        print(figure(1),'89ENF4 Test 1,2,3 Static Load vs Displacement','-dpng');
        close(1)
    elseif i==6
        title('ENF4 Test 4,5,6 Dynamic: Force vs. Displacement');
        legend({'Test 4','Test 5','Test 6'},'Location','southeast');
        print(figure(1),'93ENF4 Test 4,5,6 Dynamic Load vs Displacement','-dpng');
        close(1)
    end

    if i==1 % CHANGE POINTS BASED ON EACH TEST
        % Interpolate displacement and force at crack lengths corresponding to
timeDMG
        displacementDMG = displacement(110:254,1);
        forceDMG = force(110:254,1);
        crack_prop = crack.CrackLengthEq(110:254,1);

        coeffs=polyfit(crack_prop(:,1),displacementDMG(:,1)./forceDMG(:,1),polyfit_degree);
        fit=polyval(coeffs,crack_prop);
        dDisplacementDMGdCrackLength=diff(fit)./diff(crack_prop);
    elseif i==2
        % Interpolate displacement and force at crack lengths corresponding to
timeDMG
        displacementDMG = displacement(1552:2751,1);
        forceDMG = force(1552:2751,1);
        crack_prop = crack.CrackLengthEq(1552:2751,1);
        % Linear Polyfit done at the initial big crack propagation

        coeffs=polyfit(crack_prop(:,1),displacementDMG(:,1)./forceDMG(:,1),polyfit_degree);
        fit=polyval(coeffs,crack_prop);
        dDisplacementDMGdCrackLength=diff(fit)./diff(crack_prop);
    elseif i==3
        % Interpolate displacement and force at crack lengths corresponding to
timeDMG
        displacementDMG = displacement(1543:2615,1);
        forceDMG = force(1543:2615,1);

```

```

        crack_prop = crack.CrackLengthEq(1543:2615,1);
        % Linear Polyfit done at the initial big crack propagation between image 88
and 117
coeffs=polyfit(crack_prop(:,1),displacementDMG(:,1)./forceDMG(:,1),polyfit_degree);
        fit=polyval(coeffs,crack_prop);
        dDisplacementDMGdCrackLength=diff(fit)./diff(crack_prop);
    end

    %% Plot of Crack Length vs Displacement
    figure(2)
    set(figure(2), 'Position', figPos);
    hold on
    if i==1 || i==4
        plot(displacementDMG, crack_prop,'Color',[0.8 0 0],'LineWidth',1.5);
    elseif i==2 || i==5
        plot(displacementDMG, crack_prop,'Color',[0 0.8 0],'LineWidth',1.5);
    elseif i==3 || i==6
        plot(displacementDMG, crack_prop,'Color',[0 0 0.8],'LineWidth',1.5);
    end
    grid on
    grid minor
    xlabel('Displacement [mm]');
    ylabel('Crack Length [mm]');
    if i==3
        title('ENF4 Test 1,2,3 Static: Crack Length vs. Displacement');
        legend({'Test 1','Test 2','Test 3'},'Location','southeast');
        print(figure(2),'90ENF4 Test 1,2,3 Static Crack vs Displacement','-dpng');
        close(2)
    elseif i==6
        title('ENF4 Test 4,5,6 Dynamic: Crack Length vs. Displacement');
        legend({'Test 4','Test 5','Test 6'},'Location','southeast');
        print(figure(2),'94ENF4 Test 4,5,6 Dynamic Crack vs Displacement','-dpng');
        close(2)
    end

    %% Plot of Compliance vs Crack Length
    figure(3)
    set(figure(3), 'Position', figPos);
    hold on
    if i==1 || i==4
        plot(crack_prop, displacementDMG./forceDMG,'Color',[0.8 0
0], 'LineWidth',1.5);
    elseif i==2 || i==5
        plot(crack_prop, displacementDMG./forceDMG,'Color',[0 0.8
0], 'LineWidth',1.5);
    elseif i==3 || i==6
        plot(crack_prop, displacementDMG./forceDMG,'Color',[0 0
0.8], 'LineWidth',1.5);
    end
    grid on
    grid minor
    xlabel('Crack Length [mm]');
    ylabel('Compliance [mm/N]');
    if i==3
        title('ENF4 Test 1,2,3 Static: Compliance vs. Crack Length');
        legend({'Test 1','Test 2','Test 3'},'Location','southeast');
        print(figure(3),'91ENF4 Test 1,2,3 Static Compliance vs Crack (zona
principal)', '-dpng');
        close(3)
    elseif i==6

```

```

        title('ENF4 Test 4,5,6 Dynamic: Compliance vs. Crack Length');
        legend({'Test 4','Test 5','Test 6'},'Location','southeast');
        print(ffigure(3),'95ENF4 Test 4,5,6 Dynamic Compliance vs Crack (zona
principal)', '-dpng');
        close(3)
    end

    %% Plot the ERR per crack length - R-Curve
    figure(4)
    set(ffigure(4), 'Position', figPos);
    hold on
    if i==1 || i==4
        plot(crack_prop(1:end-1,1), dDisplacementDMGdCrackLength .* forceDMG(1:end-
1,1).^2./(2*b), 'Color',[0.8 0 0], 'LineWidth',1.5);
    elseif i==2 || i==5
        plot(crack_prop(1:end-1,1), dDisplacementDMGdCrackLength .* forceDMG(1:end-
1,1).^2./(2*b), 'Color',[0 0.8 0], 'LineWidth',1.5);
    elseif i==3 || i==6
        plot(crack_prop(1:end-1,1), dDisplacementDMGdCrackLength .* forceDMG(1:end-
1,1).^2./(2*b), 'Color',[0 0 0.8], 'LineWidth',1.5);
    end
    xlim([min_crack 135+5]);
    ylim([0 8]);
    grid on
    grid minor
    xlabel('Crack Length [mm]');
    ylabel('GII [MPa.mm]');
    if i==3
        title('ENF4 Test 1,2,3 Static: R-Curve');
        legend({'Test 1','Test 2','Test 3'},'Location','southeast');
        print(ffigure(4),'92ENF4 Test 1,2,3 Static R-Curve', '-dpng');
        close(4)
    elseif i==6
        title('ENF4 Test 4,5,6 Dynamic: R-Curve');
        legend({'Test 4','Test 5','Test 6'},'Location','southeast');
        print(ffigure(4),'96ENF4 Test 4,5,6 Static R-Curve', '-dpng');
        close(4)
    end
end
end
%% Experimental 95% curve all together

for i=1:length(experimental_file)/3
    % Data for the first test
    data1=readtable(experimental_file{(i-1)*3+1});
    time1=data1(:,1);
    nan_rows=any(isnan(time1{:,:}),2);
    time1(nan_rows,:)=[];
    disp1=data1(:,2);
    nan_rows=any(isnan(disp1{:,:}),2);
    disp1(nan_rows,:)=[];
    force1=data1(:,3);
    nan_rows=any(isnan(force1{:,:}),2);
    force1(nan_rows,:)=[];
    crack1=data1(:,4);
    nan_rows=any(isnan(crack1{:,:}),2);
    crack1(nan_rows,:)=[];

    % Data for the second test
    data2=readtable(experimental_file{(i-1)*3+2});
    time2=data2(:,1);
    nan_rows=any(isnan(time2{:,:}),2);

```

```

time2(nan_rows,:)=[];
disp2=data2(:,2);
nan_rows=any(isnan(disp2{:,:}),2);
disp2(nan_rows,:)=[];
force2=data2(:,3);
nan_rows=any(isnan(force2{:,:}),2);
force2(nan_rows,:)=[];
crack2=data2(:,4);
nan_rows=any(isnan(crack2{:,:}),2);
crack2(nan_rows,:)=[];

%Data for the third test
data3=readtable(experimental_file{(i-1)*3+3});
time3=data3(:,1);
nan_rows=any(isnan(time3{:,:}),2);
time3(nan_rows,:)=[];
disp3=data3(:,2);
nan_rows=any(isnan(disp3{:,:}),2);
disp3(nan_rows,:)=[];
force3=data3(:,3);
nan_rows=any(isnan(force3{:,:}),2);
force3(nan_rows,:)=[];
crack3=data3(:,4);
nan_rows=any(isnan(crack3{:,:}),2);
crack3(nan_rows,:)=[];

if i==1 || i==2 %%%%%%%%%% SEPARATE WHEN DYNAMIC TESTS ARE DONE
    %Join the tables into a matrix
    disp_all=[table2array(disp1(:,1)); table2array(disp2(:,1));
table2array(disp3(:,1))];
    force_all=[table2array(force1(:,1)); table2array(force2(:,1));
table2array(force3(:,1))];
    disp_space=linspace(min(disp_all),max(disp_all),2000);

    % Here the crack is the main part that we want CHECK EVERY TEST ZONES
    disp_DMG_all = [table2array(disp1(110:254,1));
table2array(disp2(1552:2751,1)); table2array(disp3(1543:2615,1))];
    force_DMG_all = [table2array(force1(110:254,1));
table2array(force2(1552:2751,1)); table2array(force3(1543:2615,1))];
    crack_DMG_all = [table2array(crack1(110:254,1));
table2array(crack2(1552:2751,1)); table2array(crack3(1543:2615,1))];
    disp_DMG_space=linspace(min(disp_DMG_all),max(disp_DMG_all),2000);
    crack_DMG_space=linspace(min(crack_DMG_all),max(crack_DMG_all),2000);

    % Compute the fits for the force and the crack per displacement
    force_coeffs=polyfit(disp_all,force_all,polyfit_degree_95_F_disp);
    force_fit=polyval(force_coeffs,disp_space);
    crack_coeffs=polyfit(disp_DMG_all,crack_DMG_all,polyfit_degree_95_a_disp);
    crack_fit=polyval(crack_coeffs,disp_DMG_space);

compliance_coeffs=polyfit(crack_DMG_all,disp_DMG_all./force_DMG_all,polyfit_degree_9
5_C_a);
    compliance_fit=polyval(compliance_coeffs,crack_DMG_space);

    % Here the crack is the main LINEAR part that we want
    % Linear Polyfit done at the initial big crack propagation between
    disp_DMG_linear = [table2array(disp1(110:254,1));
table2array(disp2(1552:2751,1)); table2array(disp3(1543:2615,1))];
    force_DMG_linear = [table2array(force1(110:254,1));
table2array(force2(1552:2751,1)); table2array(force3(1543:2615,1))];

```

```

        crack_DMG_linear = [table2array(crack1(110:254,1));
table2array(crack2(1552:2751,1)); table2array(crack3(1543:2615,1))];

crack_DMG_space_linear=linspace(min(crack_DMG_linear),max(crack_DMG_linear),2000);

        % Compute the fits for the compliance and its derivative per crack length
        % Linear Polyfit done at the initial big crack propagation between image 88
and 117

compliance_linear_coeffs=polyfit(crack_DMG_linear,disp_DMG_linear./force_DMG_linear,
polyfit_degree);
        compliance_linear_fit=polyval(compliance_linear_coeffs,crack_DMG_all);

dDisplacementDMGdCrackLength=diff(compliance_linear_fit)./diff(crack_DMG_all);
        R_coeffs=polyfit(crack_DMG_all(1:end-
1),dDisplacementDMGdCrackLength.*force_DMG_all(1:end-
1).^2./(2*b),polyfit_degree_95_R_curve);
        R_fit=polyval(R_coeffs,crack_DMG_space);

        % Derivative for each test

compliance_linear_coeffs_1=polyfit(table2array(crack1(110:254,1)),table2array(disp1(
110:254,1))./table2array(force1(110:254,1)),polyfit_degree);

compliance_linear_fit_1=polyval(compliance_linear_coeffs_1,table2array(crack1(110:25
4,1)));

dDisplacementDMGdCrackLength_1=diff(compliance_linear_fit_1)./diff(table2array(crack
1(110:254,1)));

compliance_linear_coeffs_2=polyfit(table2array(crack2(1552:2751,1)),table2array(disp
2(1552:2751,1))./table2array(force2(1552:2751,1)),polyfit_degree);

compliance_linear_fit_2=polyval(compliance_linear_coeffs_2,table2array(crack2(1552:2
751,1)));

dDisplacementDMGdCrackLength_2=diff(compliance_linear_fit_2)./diff(table2array(crack
2(1552:2751,1)));

compliance_linear_coeffs_3=polyfit(table2array(crack3(1543:2615,1)),table2array(disp
3(1543:2615,1))./table2array(force3(1543:2615,1)),polyfit_degree);

compliance_linear_fit_3=polyval(compliance_linear_coeffs_3,table2array(crack3(1543:2
615,1)));

dDisplacementDMGdCrackLength_3=diff(compliance_linear_fit_3)./diff(table2array(crack
3(1543:2615,1)));
end

        % Compute confidence interval FOR FORCE VS DISP
p = 0.95; % Confidence level
n = numel(disp_all); % Number of data points
df = n - 1; % Degrees of freedom

```

```

se = sqrt(sum((force_all - polyval(force_coeffs,disp_all)).^2) / df); %
Standard error
ts = tinv([(1-p)/2, 1-(1-p)/2], df); % t-score for confidence interval
ci = se .* ts'; % Confidence interval

figure(6)
set(figure(6), 'Position', figPos);
hold on
if i==1
    fill([disp_space, fliplr(disp_space)], [force_fit+ci(1),
fliplr(force_fit+ci(2))], [1, 0.94, 0.9], 'LineStyle', 'none'); % Confidence area
    plot(disp_space,force_fit,'Color',[1 0.5 0], 'LineWidth', 2.5);
else
    fill([disp_space, fliplr(disp_space)], [force_fit+ci(1),
fliplr(force_fit+ci(2))], [0.94, 0.9, 1], 'LineStyle', 'none'); % Confidence area
    plot(disp_space,force_fit,'Color',[0.6 0.2 1], 'LineWidth', 2.5);
end
plot(disp1{:,1},force1{:,1},'Color',[0.8 0 0], 'LineWidth', 1);
plot(disp2{:,1},force2{:,1},'Color',[0 0.8 0], 'LineWidth', 1);
plot(disp3{:,1},force3{:,1},'Color',[0 0 0.8], 'LineWidth', 1);
grid on
grid minor
xlabel('Displacement [mm]');
ylabel('Force [N]');
if i==1
    f=1;
    ENF4_Analytical % Analytical reader
    title('ENF4 95% Confidence Static: Force vs. Displacement');
    legend({'95% Confidence area','Fit Curve','Test 1','Test 2','Test
3','Analytical'},'Location','southeast');
    print(figure(6),'ENF4 95% Static Load vs Displacement','-dpng');
    close(6)
end
%%
% Compute confidence interval FOR CRACK VS DISPLACEMENT
p1 = 0.95; % Confidence level
n1 = numel(disp_DMG_all); % Number of data points
df1 = n1 - 1; % Degrees of freedom
se1 = sqrt(sum((crack_DMG_all - polyval(crack_coeffs,disp_DMG_all)).^2) / df1);
% Standard error
ts1 = tinv([(1-p1)/2, 1-(1-p1)/2], df1); % t-score for confidence interval
ci1 = se1 .* ts1'; % Confidence interval

figure(7)
set(figure(7), 'Position', figPos);
hold on
if i==1
    fill([disp_DMG_space, fliplr(disp_DMG_space)], [crack_fit+ci1(1),
fliplr(crack_fit+ci1(2))], [1, 0.94, 0.9], 'LineStyle', 'none'); % Confidence area
    plot(disp_DMG_space,crack_fit,'Color',[1 0.5 0], 'LineWidth', 2.5);
else
    fill([disp_DMG_space, fliplr(disp_DMG_space)], [crack_fit+ci1(1),
fliplr(crack_fit+ci1(2))], [0.94, 0.9, 1], 'LineStyle', 'none'); % Confidence area
    plot(disp_DMG_space,crack_fit,'Color',[0.6 0.2 1], 'LineWidth', 2.5);
end
plot(disp1{110:254,1},crack1{110:254,1},'Color',[0.8 0 0], 'LineWidth', 1);
plot(disp2{1552:2751,1},crack2{1552:2751,1},'Color',[0 0.8 0], 'LineWidth', 1);
plot(disp3{1543:2615,1},crack3{1543:2615,1},'Color',[0 0 0.8], 'LineWidth', 1);
grid on
grid minor
xlabel('Displacement [mm]');

```

```

ylabel('Crack Length [mm]');
if i==1
    f=2;
    ENF4_Analytical % Analytical reader
    title('ENF4 95% Confidence Static: Crack Length vs. Displacement');
    legend({'95% Confidence area','Fit Curve','Test 1','Test 2','Test
3','Analytical'},'Location','southeast');
    print(ffigure(7),'ENF4 95% Static Crack vs Displacement','-dpng');
    close(7)
end

%% Compute confidence interval FOR COMPLIANCE VS CRACK LENGTH
p2 = 0.95; % Confidence level
n2 = numel(crack_DMG_all); % Number of data points
df2 = n2 - 1; % Degrees of freedom
se2 = sqrt(sum(((disp_DMG_all./force_DMG_all) -
polyval(compliance_coeffs,crack_DMG_all)).^2) / df2); % Standard error
ts2 = tinv([(1-p2)/2, 1-(1-p2)/2], df2); % t-score for confidence interval
ci2 = se2 .* ts2'; % Confidence interval

figure(8)
set(figure(8), 'Position', figPos);
hold on
if i==1
    fill([crack_DMG_space, fliplr(crack_DMG_space)], [compliance_fit+ci2(1),
fliplr(compliance_fit+ci2(2))], [1, 0.94, 0.9], 'LineStyle', 'none'); % Confidence
area
    plot(crack_DMG_space,compliance_fit,'Color',[1 0.5 0], 'LineWidth', 2.5);
else
    fill([crack_DMG_space, fliplr(crack_DMG_space)], [compliance_fit+ci2(1),
fliplr(compliance_fit+ci2(2))], [0.94, 0.9, 1], 'LineStyle', 'none'); % Confidence
area
    plot(crack_DMG_space,compliance_fit,'Color',[0.6 0.2 1], 'LineWidth', 2.5);
end
plot(crack1{110:254,1},disp1{110:254,1}./force1{110:254,1},'Color',[0.8 0 0],
'LineWidth', 1);
plot(crack2{1552:2751,1},disp2{1552:2751,1}./force2{1552:2751,1},'Color',[0 0.8
0], 'LineWidth', 1);
plot(crack3{1543:2615,1},disp3{1543:2615,1}./force3{1543:2615,1},'Color',[0 0
0.8], 'LineWidth', 1);
grid on
grid minor
ylabel('Compliance [mm/N]');
xlabel('Crack Length [mm]');
if i==1
    f=3;
    ENF4_Analytical % Analytical reader
    title('ENF4 95% Confidence Static: Compliance vs. Crack Length');
    legend({'95% Confidence area','Fit Curve','Test 1','Test 2','Test
3','Analytical'},'Location','southeast');
    print(figure(8),'ENF4 95% Static Compliance vs Crack','-dpng');
    close(8)
end

%%
% Compute confidence interval FOR R-CURVE
p3 = 0.95; % Confidence level
n3 = numel(crack_DMG_all(1:end-1)); % Number of data points
df3 = n3 - 1; % Degrees of freedom

```

```

    se3 = sqrt(sum(((dDisplacementDMGdCrackLength.*force_DMG_all(1:end-1).^2./(2*b))
- polyval(R_coeffs,crack_DMG_all(1:end-1)).^2) / df3); % Standard error
    ts3 = tinv([(1-p3)/2, 1-(1-p3)/2], df3); % t-score for confidence interval
    ci3 = se3 .* ts3'; % Confidence interval

    figure(9)
    set(figure(9), 'Position', figPos);
    hold on
    if i==1
        fill([crack_DMG_space, fliplr(crack_DMG_space)], [R_fit+ci3(1),
fliplr(R_fit+ci3(2))], [1, 0.94, 0.9], 'LineStyle', 'none'); % Confidence area
        plot(crack_DMG_space,R_fit,'Color',[1 0.5 0], 'LineWidth', 2.5);
    else
        fill([crack_DMG_space, fliplr(crack_DMG_space)], [R_fit+ci3(1),
fliplr(R_fit+ci3(2))], [0.94, 0.9, 1], 'LineStyle', 'none'); % Confidence area
        plot(crack_DMG_space,R_fit,'Color',[0.6 0.2 1], 'LineWidth', 2.5);
    end
    plot(crack1{110:254-1,1},dDisplacementDMGdCrackLength_1.*force1{110:254-
1,1}.^2./(2*b),'Color',[0.8 0 0], 'LineWidth', 1);
    plot(crack2{1552:2751-1,1},dDisplacementDMGdCrackLength_2.*force2{1552:2751-
1,1}.^2./(2*b),'Color',[0 0.8 0], 'LineWidth', 1);
    plot(crack3{1543:2615-1,1},dDisplacementDMGdCrackLength_3.*force3{1543:2615-
1,1}.^2./(2*b),'Color',[0 0 0.8], 'LineWidth', 1);
    grid on
    grid minor
    ylabel('GII [MPa.mm]');
    xlabel('Crack Length [mm]');
    if i==1
        f=4;
        ENF4_Analytical % Analytical reader
        title('ENF4 95% Confidence Static: R-Curve');
        legend({'95% Confidence area','Fit Curve','Test 1','Test 2','Test
3','Analytical'},'Location','southeast');
        print(figure(9),'ENF4 95% Static R-Curve','-dpng');
        close(9)
    end

end
end

```

Next will be the subcode for analytical curves.

```

%% Data for LONG SPECIMEN
L=(95);
b=25;
h=4.7;
E11= xxxxx;
a0=50;
GIIC= xxxxx;
a_max=3/2*L;
max_linear_disp=1.5;
polyfit_degree=1;
R=8;
D=2*h^3*E11/3;
C0=L^3/(32*E11*b*h^3);
C1=9*L^2/(32*E11*b*h^3);
figPos = [100 100 780 585];
%% Calculation
time=zeros(800,1);
disp=zeros(800,1);
force=zeros(800,1);
% Linear calculation of the curve
for j=2:800

```

```

time(j,1)=time(j-1,1)+max_linear_disp/800;
disp(j,1)=time(j,1);
force(j,1)=(32*E11*b*h^3*disp(j,1))/(L^3*(1+9*a0/L));
end
% Crack propagation non-linear calculation of the curve
a=zeros(300,1);
a(1,1)=a0;
dispDMG_anal=zeros(300,1);
disp_crit=sqrt((GIIC*64*b^2*D*(C0+C1*a0)^2)/(L^2*(R-2)));
dispDMG_anal(1,1)=disp_crit;
forceDMG_anal=zeros(300,1);
force_crit=(32*E11*b*h^3*disp_crit)/(L^3*(1+9*a0/L));
forceDMG_anal(1,1)=force_crit;
timeDMG_anal=zeros(300,1);
timeDMG_anal(1,1)=dispDMG_anal(1,1);
for j=2:300
    a(j,1)=a(j-1,1)+(a_max-a0)/300;
    dispDMG_anal(j,1)=sqrt((GIIC*64*b^2*D*(C0+C1*a(j,1))^2)/(L^2*(R-2)));
    forceDMG_anal(j,1)=(32*E11*b*h^3*dispDMG_anal(j,1))/(L^3*(1+9*a(j,1)/L));
    timeDMG_anal(j,1)=dispDMG_anal(j,1);
end
disp_all=[disp; dispDMG_anal];
force_all=[force; forceDMG_anal];
if f==1
    hold on
    plot(disp_all,force_all,'k','LineStyle','--','LineWidth',1.5);
end
coeffs=polyfit(a,dispDMG_anal./forceDMG_anal,polyfit_degree);
fit=polyval(coeffs,a);
dDisplacementDMGdCrackLength_anal=diff(fit)./diff(a);

%% Plot of crack length and displacementDMG
if f==2
    hold on
    plot(dispDMG_anal, a,'k','LineStyle','--','LineWidth',1.5);
end

%% Plot of crack length and Compliance
if f==3
    hold on
    plot(a, dispDMG_anal./forceDMG_anal,'k','LineStyle','--','LineWidth',1.5);
end

%% Plot the ERR per crack length - R-Curve
if f==4
    hold on
    plot(a(2:end-1,1), dDisplacementDMGdCrackLength_anal(2:end) .*
forceDMG_anal(2:end-1).^2./(2*b),'k','LineStyle','--','LineWidth',1.5);
end

```

B.4.TAST ODB Reader

```
#####
##                               Example  Reading the ODB file                               ##
#####
# Rui Goncalves 31-03-2023
# To use in Post / Results
# Click File, choose Run Script in the menu
# import module for ABAQUS
from part import *
from material import *
from section import *
from assembly import *
from step import *
from interaction import *
from load import *
from mesh import *
from optimization import *
from job import *
from sketch import *
from visualization import *
from connectorBehavior import *
from abaqus import *
from abaqusConstants import *

import random
from array import *
from odbAccess import openOdb
import odbAccess

# import module Python

import math, numpy, time, os, shutil
from numpy import zeros,array
import csv

#=====
Nb_element = 200#n_coh_elem           # Set number of cohesive element
b           = 25
crack       = 8.0#crack_size
name="Static-Stress"
elemID = list(range(1401, 5381, 20))
#=====
# Direction for both jobs
direction=['Warp','Weft']
# Get the stress components S12 and S22
stress_components = ['S12','S22']
for x in direction:
    odbname='/Job-'+str(x)+'-Static-Stress'    # Name of the ODB file
    # PATH
    path_cwd = os.getcwd()
    myodbpath = path_cwd+odbname+'.odb'
    odb = openOdb(myodbpath)
    # Example here save Load-time and displacement-time on the RP1 point
    declare in the assembly
    step1 = odb.steps['Step-'+name]
    region_node = step1.historyRegions['Node ASSEMBLY.1']
```

```

FlData = region_node.historyOutputs['RF1'].data
u1Data = region_node.historyOutputs['U1'].data

Stress_crack_line = {}
Strain_crack_line = {}
le12data1 = {}
le12data2 = {}
le12data3 = {}
le12data4 = {}
s12data1 = {}
s12data2 = {}
s12data3 = {}
s12data4 = {}
stress_avg = {}
strain_avg = {}
for j in elemID:
    region_element_1 = step1.historyRegions['Element PART-SPEC-1.'+str(j)+'
Int Point 1']
    region_element_2 = step1.historyRegions['Element PART-SPEC-1.'+str(j)+'
Int Point 2']
    region_element_3 = step1.historyRegions['Element PART-SPEC-1.'+str(j)+'
Int Point 3']
    region_element_4 = step1.historyRegions['Element PART-SPEC-1.'+str(j)+'
Int Point 4']
    le12data1[j] = region_element_1.historyOutputs['LE12'].data
    le12data2[j] = region_element_2.historyOutputs['LE12'].data
    le12data3[j] = region_element_3.historyOutputs['LE12'].data
    le12data4[j] = region_element_4.historyOutputs['LE12'].data
    s12data1[j] = region_element_1.historyOutputs['S12'].data
    s12data2[j] = region_element_2.historyOutputs['S12'].data
    s12data3[j] = region_element_3.historyOutputs['S12'].data
    s12data4[j] = region_element_4.historyOutputs['S12'].data

for i in range(len(u1Data)):
    stress_sum = 0
    strain_sum = 0
    for j in elemID:
        time, le1 = le12data1[j][i]
        time, le2 = le12data2[j][i]
        time, le3 = le12data3[j][i]
        time, le4 = le12data4[j][i]
        time, s1 = s12data1[j][i]
        time, s2 = s12data2[j][i]
        time, s3 = s12data3[j][i]
        time, s4 = s12data4[j][i]
        stress_avg = (s1+s2+s3+s4)/4
        strain_avg = (le1+le2+le3+le4)/4
        stress_sum += stress_avg
        strain_sum += strain_avg

    Stress_crack_line[i] = stress_sum / len(elemID)
    Strain_crack_line[i] = strain_sum / len(elemID)

# Get the part instance named "PART-SPEC-2"
part_instance = odb.rootAssembly.instances['PART-SPEC-2']

# Create a path object between the two nodes
path_name = 'Path-Crack-Stress'

```

```

# For component in stress_components:
o7 = session.odbs[myodbpath]
session.viewports['Viewport: 1'].setValues(displayedObject=o7)
session.Path(name=path_name, type=NODE_LIST, expression=((
    'PART-SPEC-2', (8, 2, )), ))

if x=='Warp':# MIGHT SWAP TO UMAT FRAME IF IT WORKS WELL
    session.viewports['Viewport: 1'].odbDisplay.setFrame(step=0,
frame=int(frame_break_warp_sta_el))
else:
    session.viewports['Viewport: 1'].odbDisplay.setFrame(step=0,
frame=int(frame_break_weft_sta_el))

session.viewports['Viewport: 1'].odbDisplay.setPrimaryVariable(
    variableLabel='S', outputPosition=INTEGRATION_POINT,
refinement=(COMPONENT,
    'S12'))
pth = session.paths['Path-Crack-Stress']
xy_dataS12=session.XYDataFromPath(name='S12', path=pth,
includeIntersections=True,
    projectOntoMesh=False, pathStyle=PATH_POINTS, numIntervals=10,
    projectionTolerance=0, shape=DEFORMED, labelType=NORM_DISTANCE,
    removeDuplicateXYPairs=True, includeAllElements=False)

session.viewports['Viewport: 1'].odbDisplay.setPrimaryVariable(
    variableLabel='S', outputPosition=INTEGRATION_POINT,
refinement=(COMPONENT,
    'S22'))
xy_dataS22=session.XYDataFromPath(name='S22', path=pth,
includeIntersections=True,
    projectOntoMesh=False, pathStyle=PATH_POINTS, numIntervals=10,
    projectionTolerance=0, shape=DEFORMED, labelType=NORM_DISTANCE,
    removeDuplicateXYPairs=True, includeAllElements=False)

session.viewports['Viewport: 1'].odbDisplay.setPrimaryVariable(
    variableLabel='LE', outputPosition=INTEGRATION_POINT,
refinement=(COMPONENT,
    'LE12'))
xy_dataLE12=session.XYDataFromPath(name='LE12', path=pth,
includeIntersections=True,
    projectOntoMesh=False, pathStyle=PATH_POINTS, numIntervals=10,
    projectionTolerance=0, shape=DEFORMED, labelType=NORM_DISTANCE,
    removeDuplicateXYPairs=True, includeAllElements=False)

session.viewports['Viewport: 1'].odbDisplay.setPrimaryVariable(
    variableLabel='LE', outputPosition=INTEGRATION_POINT,
refinement=(COMPONENT,
    'LE22'))
xy_dataLE22=session.XYDataFromPath(name='LE22', path=pth,
includeIntersections=True,
    projectOntoMesh=False, pathStyle=PATH_POINTS, numIntervals=10,
    projectionTolerance=0, shape=DEFORMED, labelType=NORM_DISTANCE,
    removeDuplicateXYPairs=True, includeAllElements=False)

# Write the csv file with every data
with open('ODB-'+str(x)+'-'+name+'-combined.csv', 'wb') as file_results:
    writer = csv.writer(file_results, delimiter=';')

```

```

writer.writerow(['time', 'disp', 'force', 'AVG S12', 'AVG LE12', 'true
dist', 'S12', 'S22', 'LE12', 'LE22'])

# Save displacement u1 and force F1
for i in range(1, len(u1Data)):
    time, u1 = u1Data[i]
    time, F1 = F1Data[i]

    if x=='Warp':
        if i<len(xy_dataS12)-1 and i<frame_break_warp_sta_el:
            # Save stress data
            true_dist, S12 = xy_dataS12[i]
            true_dist, S22 = xy_dataS22[i]
            true_dist, LE12 = xy_dataLE12[i]
            true_dist, LE22 = xy_dataLE22[i]
            writer.writerow(['%10.6E' % (time/1000000), '%10.6E' %
(u1/1000000), '%10.6E' % (F1*b/1000000), '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' %
(Strain_crack_line[i]/1000000), '%10.6E' % ((true_dist*2-1)/1000000), '%10.6E'
% (S12/1000000), '%10.6E' % (S22/1000000), '%10.6E' % (LE12/1000000), '%10.6E' %
(LE22/1000000))])
        elif i<len(xy_dataS12)-1 and i>frame_break_warp_sta_el:
            writer.writerow([0,0,0, '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' %
(Strain_crack_line[i]/1000000), '%10.6E' % ((true_dist*2-1)/1000000), '%10.6E'
% (S12/1000000), '%10.6E' % (S22/1000000))])
        elif i>len(xy_dataS12)-1 and i<frame_break_warp_sta_el:
            writer.writerow(['%10.6E' % (time/1000000), '%10.6E' %
(u1/1000000), '%10.6E' % (F1*b/1000000), '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' % (Strain_crack_line[i]/1000000)])
    else:
        if i<len(xy_dataS12)-1 and i<frame_break_weft_sta_el:
            # Save stress data
            true_dist, S12 = xy_dataS12[i]
            true_dist, S22 = xy_dataS22[i]
            true_dist, LE12 = xy_dataLE12[i]
            true_dist, LE22 = xy_dataLE22[i]
            writer.writerow(['%10.6E' % (time/1000000), '%10.6E' %
(u1/1000000), '%10.6E' % (F1*b/1000000), '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' %
(Strain_crack_line[i]/1000000), '%10.6E' % ((true_dist*2-1)/1000000), '%10.6E'
% (S12/1000000), '%10.6E' % (S22/1000000), '%10.6E' % (LE12/1000000), '%10.6E' %
(LE22/1000000))])
        elif i<len(xy_dataS12)-1 and i>frame_break_weft_sta_el:
            writer.writerow([0,0,0, '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' %
(Strain_crack_line[i]/1000000), '%10.6E' % ((true_dist*2-1)/1000000), '%10.6E'
% (S12/1000000), '%10.6E' % (S22/1000000))])
        elif i>len(xy_dataS12)-1 and i<frame_break_weft_sta_el:
            writer.writerow(['%10.6E' % (time/1000000), '%10.6E' %
(u1/1000000), '%10.6E' % (F1*b/1000000), '%10.6E' %
(Stress_crack_line[i]/1000000), '%10.6E' % (Strain_crack_line[i]/1000000)])
# END OF FILE
#=====

```

B.5.Numerical TAST MATLAB

```

clear
clc
close all

name=["Warp-Static-Stress" "Weft-Static-Stress"];
numFiles=length(name);
fileNames=cell(numFiles,1);
delimiter=';';
b=25; %Width
figPos = [100 100 780 585];
%% Files from Static Cohesive elements and surfaces to compare with Static Stress on
Force vs Disp only
fileNames_Warp={'ODB-Warp-Static-El-combined.csv';'ODB-Warp-Static-Surf-
combined.csv';'ODB-Warp-Static-El-UMAT-combined.csv'};
data_static_warp_el=readtable(fileNames_Warp{1}, 'Delimiter', delimiter);
time_static_warp_el=data_static_warp_el(:,1);
disp_static_warp_el=data_static_warp_el(:,2);
force_static_warp_el=data_static_warp_el(:,3);
data_static_warp_surf=readtable(fileNames_Warp{2}, 'Delimiter', delimiter);
time_static_warp_surf=data_static_warp_surf(:,1);
disp_static_warp_surf=data_static_warp_surf(:,2);
force_static_warp_surf=data_static_warp_surf(:,3);
data_static_warp_umat=readtable(fileNames_Warp{3}, 'Delimiter', delimiter);
time_static_warp_umat=data_static_warp_umat(:,1);
disp_static_warp_umat=data_static_warp_umat(:,2);
force_static_warp_umat=data_static_warp_umat(:,3);
data_dynamic_warp_umat=readtable(fileNames_Warp{4}, 'Delimiter', delimiter);
time_dynamic_warp_umat=data_dynamic_warp_umat(:,1);
disp_dynamic_warp_umat=data_dynamic_warp_umat(:,2);
force_dynamic_warp_umat=data_dynamic_warp_umat(:,3);
fileNames_Weft={'ODB-Weft-Static-El-combined.csv';'ODB-Weft-Static-Surf-
combined.csv';'ODB-Weft-Static-El-UMAT-combined.csv';'ODB-Weft-Dynamic-El-UMAT-
combined.csv'};
data_static_weft_el=readtable(fileNames_Weft{1}, 'Delimiter', delimiter);
time_static_weft_el=data_static_weft_el(:,1);
disp_static_weft_el=data_static_weft_el(:,2);
force_static_weft_el=data_static_weft_el(:,3);
data_static_weft_surf=readtable(fileNames_Weft{2}, 'Delimiter', delimiter);
time_static_weft_surf=data_static_weft_surf(:,1);
disp_static_weft_surf=data_static_weft_surf(:,2);
force_static_weft_surf=data_static_weft_surf(:,3);
data_static_weft_umat=readtable(fileNames_Weft{3}, 'Delimiter', delimiter);
time_static_weft_umat=data_static_weft_umat(:,1);
disp_static_weft_umat=data_static_weft_umat(:,2);
force_static_weft_umat=data_static_weft_umat(:,3);
data_dynamic_weft_umat=readtable(fileNames_Weft{4}, 'Delimiter', delimiter);
time_dynamic_weft_umat=data_dynamic_weft_umat(:,1);
disp_dynamic_weft_umat=data_dynamic_weft_umat(:,2);
force_dynamic_weft_umat=data_dynamic_weft_umat(:,3);
for i=1:numFiles
    fileNames{i}=['ODB-', char(name(i)), '-combined.csv'];
end
for i=1:numFiles
    %% Retrieve the data for each different file
    data=readtable(fileNames{i}, 'Delimiter', delimiter);
    time=data(:,1);
    disp=data(:,2);

```

```

disp{end+1,:}=disp{end,:}*2-disp{end-1,:};
force=data(:,3);
force{end+1,:}=0;
avg_stress=data(:,4);
avg_strain=data(:,5);
true_dist=data(:,6);
nan_rows=any(isnan(true_dist{:,:}),2);
true_dist(nan_rows,:)=[];
S12=data(:,7);
nan_rows=any(isnan(S12{:,:}),2);
S12(nan_rows,:)=[];
S22=data(:,8);
nan_rows=any(isnan(S22{:,:}),2);
S22(nan_rows,:)=[];
LE12=data(:,9);
nan_rows=any(isnan(LE12{:,:}),2);
LE12(nan_rows,:)=[];
LE22=data(:,10);
nan_rows=any(isnan(LE22{:,:}),2);
LE22(nan_rows,:)=[];
%% Plot of displacement and force
figure(1)
set(figure(1), 'Position', figPos);
hold on
if i==1 || i==3
    plot(disp{:,:}*1000000, force{:,:}*1000000, 'Color',[0 0 0], 'LineWidth',1.5);
elseif i==2 || i==4
    plot(disp{:,:}*1000000, force{:,:}*1000000, 'Color',[0 0
0], 'LineWidth',1.5, 'LineStyle',':');
end
if i==1
    plot(disp_static_warp_surf{:,:}*1000000,
force_static_warp_surf{:,:}*1000000, 'Color',[0.8 0
0], 'LineWidth',1.5, 'LineStyle',':');
    plot(disp_static_warp_el{:,:}*1000000,
force_static_warp_el{:,:}*1000000, 'Color',[0 0.8 0], 'LineWidth',1.5, 'LineStyle','-
. ');
    plot(disp_static_warp_umat{:,:}*1000000,
force_static_warp_umat{:,:}*1000000, 'Color',[0 0 0.8], 'LineWidth',1.5)
elseif i==3
    plot(disp_dynamic_warp_umat{:,:}*1000000,
force_dynamic_warp_umat{:,:}*1000000, 'Color',[0 0
0.8], 'LineWidth',1.5, 'LineStyle',': ')
elseif i==2
    plot(disp_static_weft_surf{:,:}*1000000,
force_static_weft_surf{:,:}*1000000, 'Color',[0.8 0
0], 'LineWidth',1.5, 'LineStyle',': ');
    plot(disp_static_weft_el{:,:}*1000000,
force_static_weft_el{:,:}*1000000, 'Color',[0 0.8 0], 'LineWidth',1.5, 'LineStyle','-
. ');
    plot(disp_static_weft_umat{:,:}*1000000,
force_static_weft_umat{:,:}*1000000, 'Color',[0 0 0.8], 'LineWidth',1.5)
elseif i==4
    plot(disp_dynamic_weft_umat{:,:}*1000000,
force_dynamic_weft_umat{:,:}*1000000, 'Color',[0 0
0.8], 'LineWidth',1.5, 'LineStyle',': ')
end
hold off
grid on
grid minor
xlabel('Displacement [mm]');

```

```

ylabel('Force [N]');
if i==1
    title('TAST Warp Static: Force vs. Displacement');
    legend({'Static without Failure','Static Coh. Surf.','Static Coh.
Ekem.','Static UMAT'},'Location','northwest');
    print(ffigure(1),'18TAST El, Surf, UMAT, Stress Warp Static Load vs
Displacement','-dpng');
    close(1)
elseif i==3
    title('TAST Warp Dynamic: Force vs. Displacement');
    legend({'Dynamic Stress','Dynamic UMAT'},'Location','northwest');
    print(ffigure(1),'22TAST UMAT, Stress Warp Dynamic Load vs Displacement','-
dpng');
    close(1)
elseif i==2
    title('TAST Weft Static: Force vs. Displacement');
    legend({'Static without Failure','Static Coh. Surf.','Static Coh.
Elem.','Static UMAT'},'Location','northwest');
    print(ffigure(1),'51TAST El, Surf, UMAT, Stress Weft Static Load vs
Displacement','-dpng');
    close(1)
elseif i==4
    title('TAST Stress Weft Dynamic: Force vs. Displacement');
    legend({'Dynamic Stress','Dynamic UMAT'},'Location','northwest');
    print(ffigure(1),'55TAST Stress Weft Dynamic Load vs Displacement','-dpng');
    close(1)
end
%% Plot of STRAIN 12 and 22 and true_dist
figure(3)
set(figure(3), 'Position', figPos);
hold on
if i==1 || i==3
    plot(true_dist{:, :}*1000000, LE22{:, :}*1000000, 'Color',[0 0
0.5], 'LineWidth',1.5);
    plot(true_dist{:, :}*1000000, LE12{:, :}*1000000, 'Color',[0.6 0
0], 'LineWidth',1.5);
elseif i==2 || i==4
    plot(true_dist{:, :}*1000000, LE22{:, :}*1000000, 'Color',[0.1 0.3
1], 'LineStyle','--', 'LineWidth',1.5);
    plot(true_dist{:, :}*1000000, LE12{:, :}*1000000, 'Color',[1 0
0], 'LineStyle','--', 'LineWidth',1.5);
end
grid on
grid minor
xlabel('True Distance [-]');
ylabel('Strain [-]');
if i==1
    title('TAST Warp Static: Strain vs. True Distance');
    legend({'LE22','LE12'},'Location','northeast');
    print(ffigure(3),'20TAST Stress Warp Static Strain 12 22 on crack line','-
dpng');
    close(3)
elseif i==3
    title('TAST Warp Dynamic: Strain vs. True Distance');
    legend({'Dynamic 1m/s LE22','Dynamic 1m/s LE12'},'Location','northeast');
    print(ffigure(3),'24TAST Stress Warp Dynamic Strain 12 22 on crack line','-
dpng');
    close(3)
elseif i==2
    title('TAST Weft Static: Strain vs. True Distance');
    legend({'LE22','LE12'},'Location','northeast');

```

```

        print(ffigure(3),'53TAST Stress Weft Static Strain 12 22 on crack line','-
dpng');
        close(3)
        elseif i==4
            title('TAST Weft Dynamic: Strain vs. True Distance');
            legend({'Dynamic 1m/s LE22','Dynamic 1m/s LE12'},'Location','northeast');
            print(ffigure(3),'57TAST Stress Weft Dynamic Strain 12 22 on crack line','-
dpng');
            close(3)
        end
%% Plot of STRESS 12 and 22 and true_dist
figure(5)
set(ffigure(5), 'Position', figPos);
hold on
if i==1 || i==3
    plot(true_dist{:, :}*1000000, S22{:, :}*1000000, 'Color',[0 0
0.5], 'LineWidth',1.5);
    plot(true_dist{:, :}*1000000, S12{:, :}*1000000, 'Color',[0.6 0
0], 'LineWidth',1.5);
    elseif i==2 || i==4
        plot(true_dist{:, :}*1000000, S22{:, :}*1000000, 'Color',[0.1 0.3
1], 'LineStyle','--', 'LineWidth',1.5);
        plot(true_dist{:, :}*1000000, S12{:, :}*1000000, 'Color',[1 0 0], 'LineStyle','-
-', 'LineWidth',1.5);
    end
    grid on
    grid minor
    xlabel('True Distance [-]');
    ylabel('Stress [MPa]');
    if i==1
        title('TAST Warp Static: Stress vs. True Distance');
        legend({'S22','S12'},'Location','northeast');
        print(ffigure(5),'21TAST Stress Warp Static Stress 12 22 on crack line','-
dpng');
        close(5)
    elseif i==3
        title('TAST Warp Dynamic: Stress vs. True Distance');
        legend({'Dynamic 1m/s S22','Dynamic 1m/s S12'},'Location','northeast');
        print(ffigure(5),'25TAST Stress Warp Dynamic Stress 12 22 on crack line','-
dpng');
        close(5)
    elseif i==2
        title('TAST Weft Static: Stress vs. True Distance');
        legend({'S22','S12'},'Location','northeast');
        print(ffigure(5),'54TAST Stress Weft Static Stress 12 22 on crack line','-
dpng');
        close(5)
    elseif i==4
        title('TAST Weft Dynamic: Stress vs. True Distance');
        legend({'Dynamic 1m/s S22','Dynamic 1m/s S12'},'Location','northeast');
        print(ffigure(5),'58TAST Stress Weft Dynamic Stress 12 22 on crack line','-
dpng');
        close(5)
    end
%% Plot of Average S12 and LE12 along the crack line
avg_coeffs=polyfit(table2array(avg_strain),table2array(avg_stress),1);
figure(7)
set(ffigure(7), 'Position', figPos);
hold on
if i==1 || i==3

```

```

        plot(avg_strain{:, :}*1000000, avg_stress{:, :}*1000000, 'Color', [0 0
0], 'LineWidth', 1.5);
    elseif i==2 || i==4
        plot(avg_strain{:, :}*1000000, avg_stress{:, :}*1000000, 'Color', [0 0
0], 'LineWidth', 1.5, 'LineStyle', ':');
    end
    hold off
    grid on
    grid minor
    xlabel('Strain [-]');
    ylabel('Stress [MPa]');
    if i==1
        txt1 = ['Stress = ' num2str(round(avg_coeffs(1),2)) '*Strain + '
num2str(round(avg_coeffs(2),4)) '];
        text(6*10^-3, 25, txt1, 'FontSize', 12, 'Color', [0 0 0], 'FontWeight',
'bold');
        title('TAST Warp Static: Shear Stress S12 vs. Shear Strain Gamma12');
        legend({'Static without Failure'}, 'Location', 'northwest');
        print(ffigure(7), '19TAST Stress Warp Static Shear Stress vs Strain (with
eq)', '-dpng');
        close(7)
    elseif i==3
        txt1 = ['Stress = ' num2str(round(avg_coeffs(1),2)) '*Strain + '
num2str(round(avg_coeffs(2),4)) '(Dynamic)'];
        text(6*10^-3, 20, txt1, 'FontSize', 12, 'Color', [0 0 0], 'FontWeight',
'bold');
        title('TAST Warp Dynamic: Shear Stress S12 vs. Shear Strain Gamma12');
        legend({'Dynamic 1ms^-1'}, 'Location', 'northwest');
        print(ffigure(7), '23TAST Stress Warp Dynamic Shear Stress vs Strain (with
eq)', '-dpng');
        close(7)
    elseif i==2
        txt1 = ['Stress = ' num2str(round(avg_coeffs(1),2)) '*Strain + '
num2str(round(avg_coeffs(2),4)) '];
        text(6*10^-3, 60, txt1, 'FontSize', 12, 'Color', [0 0 0], 'FontWeight',
'bold');
        title('TAST Weft Static: Shear Stress S13 vs. Shear Strain Gamma13');
        legend({'Static without Failure'}, 'Location', 'northwest');
        print(ffigure(7), '52TAST Stress Weft Static Shear Stress vs Strain (with
eq)', '-dpng');
        close(7)
    elseif i==4
        txt1 = ['Stress = ' num2str(round(avg_coeffs(1),2)) '*Strain + '
num2str(round(avg_coeffs(2),4)) '(Dynamic)'];
        text(6*10^-3, 55, txt1, 'FontSize', 12, 'Color', [0 0 0], 'FontWeight',
'bold');
        title('TAST Stress Weft Dynamic: Shear Stress S13 vs. Shear Strain
Gamma13');
        legend({'Dynamic 1ms^-1'}, 'Location', 'northwest');
        print(ffigure(7), '56TAST Stress Weft Dynamic Shear Stress vs Strain (with
Eqs)', '-dpng');
        close(7)
    end
end
end

```


Annex C. ELS Stability Check and Results

Figure 51 shows the drawing of the ELS test, including the stresses and moment that occur on each beam part. On the right of the stress and moment graph, the values shown are for both Part 2 and Part 3, individually. On the left, it's the values for Part 1. The diagrams are not scaled, x , y , and z are the horizontal, vertical and width direction, respectively.

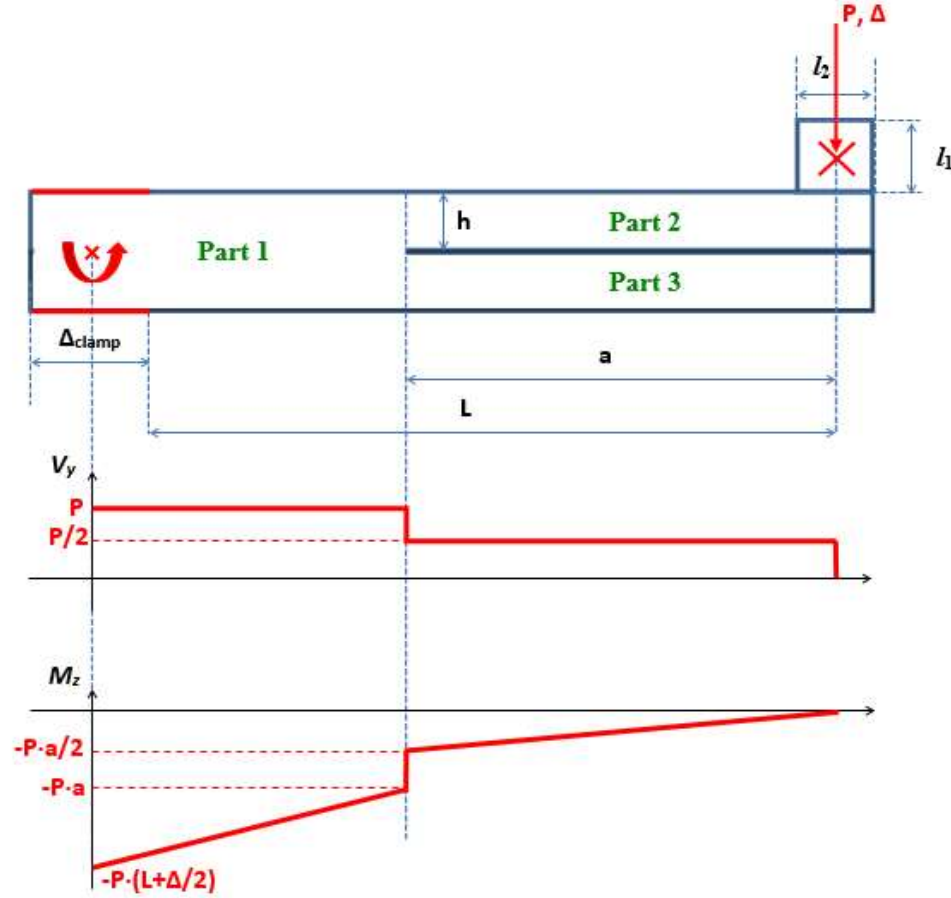


Figure 51 – ELS specimen drawing with stresses and moments of each beam part.

The energy of elastic deformation for flexion is calculated with Eq. (C.1):

$$E_{el} = \iint \frac{\sigma^2}{2E} dL_x dA \quad (C.1)$$

where A is the area of the section of the beam, $A = Bh$ for Part 2 and Part 3, $A = 2Bh$ for Part 1; L_x is the length of each beam part, E is the Young's modulus of the beam, and σ is the stress along the section of the beam, which in bending follows a linear evolution $\sigma = \alpha \cdot y$, and is calculated with Eq. (C.2)

$$\begin{aligned} M_z &= \int -y dF = - \int y \cdot \sigma dA = -\alpha \int y^2 dA = -\sigma/y \cdot I_{xx} \Leftrightarrow \\ &\Leftrightarrow \sigma = -y \cdot M_z / I_{xx} \end{aligned} \quad (C.2)$$

Integrating Eq. (C.2) in (C.1):

$$E_{el} = \iint \frac{y^2 M_z^2}{2EI_{xx}} dL_x dA = \frac{1}{2EI_{xx}} \int M_z^2 dL_x \quad (C.3)$$

For Part 2 and 3, L_x is between 0 and a , with $M_z = P \cdot x/2$, while for Part 1 L_x is between a and $(L+\Delta/2)$, with $M_z = P \cdot x$, and a thickness of $2h$. Using Eq. (C.3) the elastic energy for each part is attained, Eq. (C.4):

$$E_{el}^{Part\ 1} = \frac{P^2}{8EI_{xx}} \int_0^a x^2 dx = \frac{P^2 a^3}{2h^3 BE} \quad (C.4)$$

$$E_{el}^{Part\ 2\ \&\ 3} = \frac{P^2}{2EI_{xx}} \int_a^{L+\Delta/2} x^2 dx = \frac{P^2 \left[(L + \Delta/2)^3 - a^3 \right]}{4h^3 BE}$$

where $I_{xx} = Bh^3/12$.

The total energy of deformation of the specimen is:

$$E_{el}^{total} = E_{el}^{Part\ 1} + 2 \cdot E_{el}^{Part\ 2\ \&\ 3} = \frac{P^2 \left[(L + \Delta/2)^3 + 3a^3 \right]}{4h^3 BE} \quad (C.5)$$

Using the Castigliano's theory, the compliance is:

$$C = \frac{\delta}{P} = \frac{1}{P} \frac{\partial E_{el}^{total}}{\partial P} = \frac{3}{2h^3 BE} \cdot \left[a^3 + \frac{(L + \Delta/2)^3}{3} \right] = a^3 \cdot C_1 + C_0 \quad (C.6)$$

The DFT is then calculated through Eq. (C.7):

$$G_{II}^{ELS} = \frac{P^2}{2B} \frac{\partial C}{\partial a} = \frac{3P^2 a^2}{2B} \cdot C_1, \text{ where } C_1 = \frac{3}{2h^3 BE} \quad (C.7)$$

$$G_{II}^{ELS} = \frac{9P^2 a^2}{4B^2 h^3 E}$$

For the stability check, the $\partial G_{II}^{ELS} / \partial a$ should be negative. Changing to a displacement control, the DFT is calculated with Eq. (C.8), obtained with the Castigliano's theory and $S=C^{-1}$, which is the stiffness of the beam.

$$G_{II}^{ELS} = -\frac{\delta^2}{2B} \frac{\partial S}{\partial a} \quad (C.8)$$

where the stiffness is:

$$S = \frac{2Bh^3 E}{3a^3 + (L + \Delta/2)^3} \Rightarrow \frac{\partial S}{\partial a} = -\frac{2Bh^3 E a^2}{\left[a^3 + \frac{(L + \Delta/2)^3}{3} \right]^2} \quad (C.9)$$

Inserting Eq. (C.9) in Eq. (C.8), followed by the partial derivative according to the crack length, a , Eq. (C.10) is attained:

$$G_{II}^{ELS} = \frac{\delta^2 h^3 E a^2}{\left[a^3 + \frac{(L + \Delta/2)^3}{3} \right]^2} \Rightarrow \frac{\partial G_{II}^{ELS}}{\partial a} = 2\delta^2 h^3 E \cdot \frac{a \left[\frac{(L + \Delta/2)^3}{3} - 2a^3 \right]}{\left[a^3 + \frac{(L + \Delta/2)^3}{3} \right]^3} \quad (C.10)$$

From this equation, the $(2\delta^2 h^3 E)$ component is always positive. The same can be said about the denominator since a , L , and Δ are always positive, leaving only the numerator of the fraction. Hence, the test is stable if Eq.(C.11) is ensured.

$$\begin{aligned} \frac{\partial G_{II}^{ELS}}{\partial a} < 0 &\Leftrightarrow a \left[\frac{(L + \Delta/2)^3}{3} - 2a^3 \right] < 0 \Leftrightarrow \frac{a^3}{(L + \Delta/2)^3} > \frac{1}{6} \Leftrightarrow \\ &\Leftrightarrow \frac{a}{L + \Delta/2} > \frac{1}{\sqrt[3]{6}} \approx 0.5503 \end{aligned} \quad (C.11)$$

Therefore, if the crack length is 0.5503 times higher than the equivalent length, $L + \Delta/2$, the ELS test is stable. Furthermore, Blackman (Blackman, Brunner and Williams 2006) suggests the use of correction factors, F and N , which are the correction factors for large displacements and for bonded on end-block effects, respectively. The next set of equations displays where these factors are used, and how to calculate them.

$$G_{II}^{ELS} = \frac{9P^2 a^2}{4B^2 h^3 E} \cdot F \quad (C.12)$$

$$C = \frac{3}{2h^3 B E} \cdot \left[a^3 + \frac{(L + \Delta/2)^3}{3} \right] \cdot N \quad (C.13)$$

$$F = 1 - \theta_1 \left(\frac{\delta}{L} \right)^2 - \theta_2 \left(\frac{\delta l_1}{L^2} \right) \quad (C.14)$$

$$N = 1 - \theta_3 \left(\frac{l_2}{L} \right)^3 - \theta_4 \left(\frac{\delta l_1}{L^2} \right) - \theta_5 \left(\frac{\delta}{L} \right)^2 \quad (C.15)$$

$$\theta_1 = \frac{3}{20} \left[\frac{15 + 50 \left(\frac{a}{L} \right)^2 + 63 \left(\frac{a}{L} \right)^4}{\left[1 + 3 \left(\frac{a}{L} \right)^3 \right]^2} \right] \quad (C.16)$$

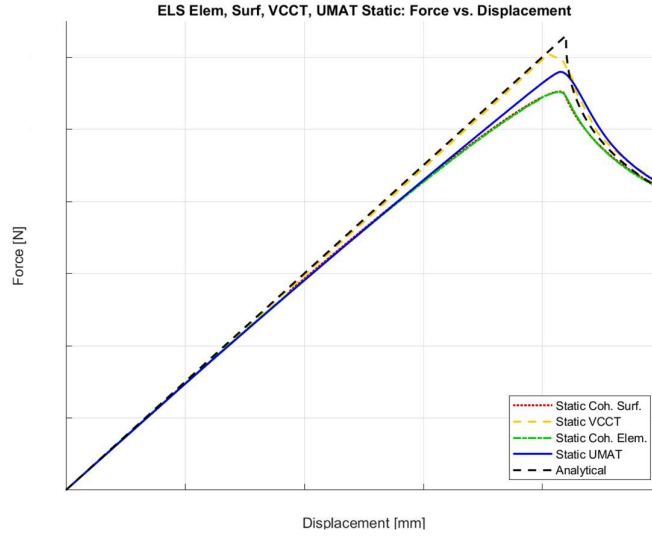
$$\theta_2 = \frac{-3 \left(\frac{L}{a} \right) \left(1 + 3 \left(\frac{a}{L} \right)^2 \right)}{1 + 3 \left(\frac{a}{L} \right)^3} \quad (C.17)$$

$$\theta_3 = \frac{4}{1 + 3 \left(\frac{a}{L} \right)^3} \quad (C.18)$$

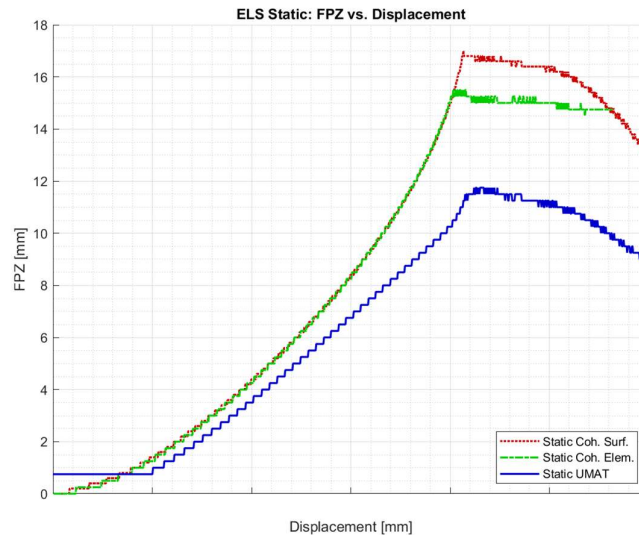
$$\theta_4 = -\frac{9}{4} \cdot \frac{\left[\left(1 - \left(\frac{a}{L}\right)\right) \left(1 + 3 \left(\frac{a}{L}\right)^3\right) + 4 \left(\frac{a}{L}\right)^2 \left(1 - \left(\frac{L_2}{a}\right)^2\right) \left(1 + 3 \left(\frac{a}{L}\right)^2\right) \right]}{\left(1 + 3 \left(\frac{a}{L}\right)^3\right)^2} \quad (\text{C.19})$$

$$\theta_5 = \frac{36}{35} \cdot \frac{1 + \frac{3}{8} \left(\frac{a}{L}\right)^3 \left(35 + 70 \left(\frac{a}{L}\right)^2 + 63 \left(\frac{a}{L}\right)^4\right)}{\left(1 + 3 \left(\frac{a}{L}\right)^3\right)^3} \quad (\text{C.20})$$

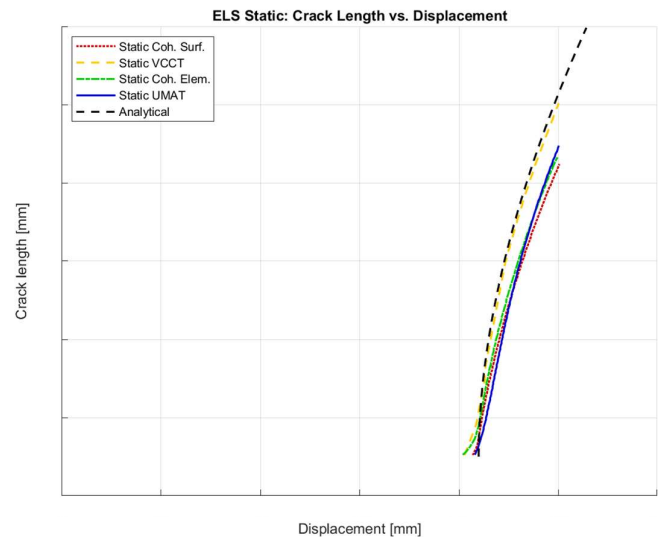
The results of the numerical analysis are now reported in the following graphs.



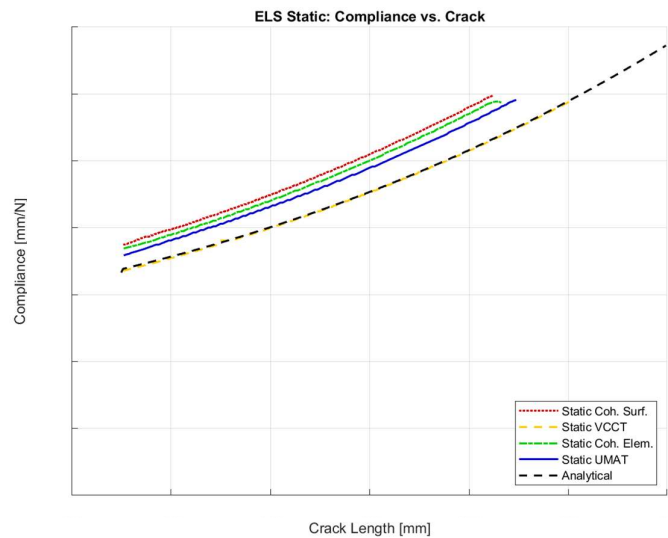
Graph 62 – ELS numerical results: Load vs Displacement.



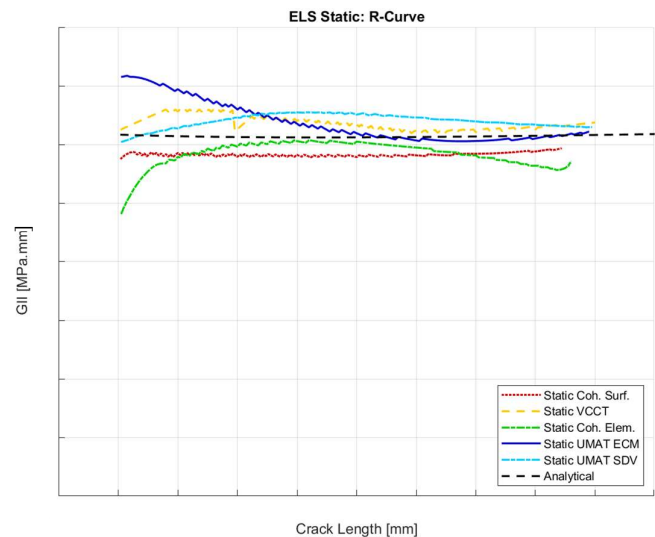
Graph 63 – ELS numerical results: FPZ vs Displacement.



Graph 64 – ELS numerical results: Crack Length vs Displacement.



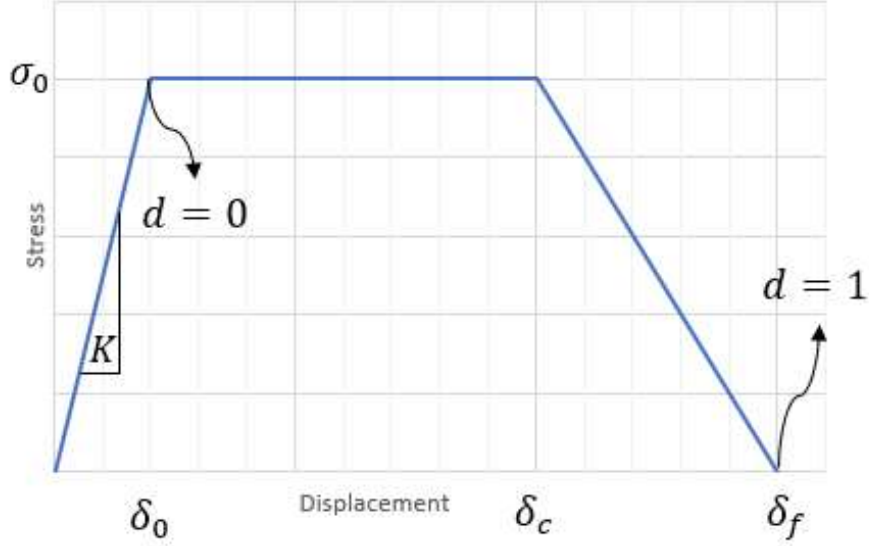
Graph 65 – ELS numerical results: Compliance vs Crack Length.



Graph 66 – ELS numerical results: R-Curve.

Annex D. New UMAT Formulation

The shape of the cohesive law is a trapeze, where δ_c changes according to the mixed mode behaviour, with the parameters as seen in Graph 67. This annex will report the by what method the UMAT formulation was arrived.



Graph 67 – Definition of parameters of the trapeze cohesive law.

As explained in Section 4.1, the damage parameter has two zones, the plateau, and the descending ramp. The stress is always calculated through Eq. (D.1):

$$\sigma = (1 - d)K\delta \quad (D.1)$$

where d is the damage, K is the stiffness of the cohesive element, and δ is the acting displacement. On the plateau, $\sigma = \sigma_0 = K\delta_0$, hence the damage can be written as:

$$\begin{aligned} \sigma_0 &= (1 - d)K\delta \Leftrightarrow \\ \Leftrightarrow d &= 1 - \frac{\sigma_0}{K\delta} = 1 - \frac{\delta_0}{\delta} \quad , \text{ for } \delta_0 \leq \delta < \delta_c \end{aligned} \quad (D.2)$$

As for the ramp, using a simple linear fit curve $y = m \cdot x + b$, the stress can be calculated with:

$$\sigma = \frac{\sigma_0}{\delta_f - \delta_c}(\delta_f - \delta) \quad (D.3)$$

Then the damage on the ramp is calculated with:

$$\begin{aligned} (1 - d)K\delta &= \frac{\sigma_0}{\delta_f - \delta_c}(\delta_f - \delta) \Leftrightarrow d = 1 - \frac{\delta_0}{\delta} \cdot \frac{(\delta_f - \delta)}{(\delta_f - \delta_c)} \Leftrightarrow \\ \Leftrightarrow d &= 1 - \frac{\delta_0}{\delta_c - \delta_f} \cdot \left(1 - \frac{\delta_f}{\delta}\right) \quad , \text{ for } \delta_c \leq \delta < \delta_f \end{aligned} \quad (D.4)$$

The displacement where the damage starts, δ_0 , can be calculated through the quadratic stress criterion, following the steps in Eqs. (D.6). For the sake of completeness, the auxiliary equations are reported here in (D.5).

$$\begin{aligned}
 \beta &= \frac{\delta^{\text{II}}}{\delta^{\text{I}}} \\
 \delta &= \sqrt{\delta^{\text{I}^2} + \delta^{\text{II}^2}} \\
 \delta^{\text{II}} &= \sqrt{\delta_{13}^2 + \delta_{23}^2} \\
 \sigma_0^i &= K^i \delta_0^i \\
 G_i &= \frac{\sigma_0^i}{2} (\delta_f^i + \delta_c^i - \delta_0^i) \\
 K &= (K^{\text{II}} - K^{\text{I}}) \frac{\beta^2}{\beta^2 + 1} + K^{\text{I}} \\
 \delta_f &= \delta_c + \frac{2G_{Ic}}{\sigma_0^{\text{I}}} - \frac{\sigma_0^{\text{I}}}{K^{\text{I}}}
 \end{aligned} \tag{D.5}$$

where $i=\text{I, II}$ is the index for the possible delaminations modes. Mode III is assumed to be together with Mode II as the shear mode. Where no index is present, it's assumed to be the equivalent mixed mode parameter.

$$\begin{aligned}
 \left(\frac{\sigma^{\text{I}}}{\sigma_0^{\text{I}}}\right)^2 + \left(\frac{\sigma^{\text{II}}}{\sigma_0^{\text{II}}}\right)^2 &= \left(\frac{\sigma}{\sigma_0}\right)^2, \text{ if } \left(\frac{\sigma}{\sigma_0}\right)^2 \geq 1, \text{ damage initiates} \\
 \left(\frac{K^{\text{I}}\delta^{\text{I}}}{K^{\text{I}}\delta_0^{\text{I}}}\right)^2 + \left(\frac{K^{\text{II}}\delta^{\text{II}}}{K^{\text{II}}\delta_0^{\text{II}}}\right)^2 &= \left(\frac{K\delta}{K\delta_0}\right)^2 \Leftrightarrow \\
 \Leftrightarrow \left(\frac{\delta^{\text{I}}}{\delta_0^{\text{I}}}\right)^2 + \left(\frac{\delta^{\text{II}}}{\delta_0^{\text{II}}}\right)^2 &= \frac{\delta^{\text{I}^2} + \delta^{\text{II}^2}}{\delta_0^2} \Leftrightarrow \\
 \Leftrightarrow \frac{\delta^{\text{I}^2}\delta_0^{\text{II}^2} + \delta^{\text{II}^2}\delta_0^{\text{I}^2}}{\delta_0^{\text{I}^2}\delta_0^{\text{II}^2}} &= \frac{\delta^{\text{I}^2} + \beta^2\delta^{\text{I}^2}}{\delta_0^2} \Leftrightarrow \\
 \Leftrightarrow \frac{\delta_0^2}{\delta_0^{\text{I}^2}\delta_0^{\text{II}^2}} &= \frac{\delta^{\text{I}^2}(1 + \beta^2)}{\delta^{\text{I}^2}(\delta_0^{\text{II}^2} + \beta^2\delta_0^{\text{I}^2})} \Leftrightarrow \\
 \Leftrightarrow \delta_0 &= \delta_0^{\text{I}}\delta_0^{\text{II}} \sqrt{\frac{1 + \beta^2}{(\delta_0^{\text{II}^2} + \beta^2\delta_0^{\text{I}^2})}} \Leftrightarrow
 \end{aligned} \tag{D.6}$$

The next step is to attain the displacement at the end of the plateau, δ_c , using the B-K Law and the auxiliary equations in (D.5). The calculation of this parameter is reported in (D.7).

$$\begin{aligned}
 G &= G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \Leftrightarrow \\
 &\Leftrightarrow \frac{\sigma_0(\delta_f + \delta_c - \delta_0)}{2} = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \Leftrightarrow \\
 &\Leftrightarrow \frac{K\delta_0(\delta_f + \delta_c - \delta_0)}{2} = G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \Leftrightarrow \\
 &\Leftrightarrow (\delta_f + \delta_c - \delta_0) = \frac{2}{K\delta_0} \left[G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \right] \Leftrightarrow \\
 &\Leftrightarrow \frac{2G_{Ic}}{\sigma_0^I} - \frac{\sigma_0^I}{K_I} + 2\delta_c - \delta_0 = \frac{2}{K\delta_0} \left[G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \right] \Leftrightarrow \\
 &\Leftrightarrow \delta_c = \frac{1}{K\delta_0} \left[G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II}}{G_T} \right)^n \right] + \frac{\delta_0}{2} + \frac{\sigma_0^I}{2K_I} - \frac{G_{Ic}}{\sigma_0^I}
 \end{aligned} \tag{D.7}$$

where $G_T = G_I + G_{II}$, so the ratio G_{II}/G_T can be reached with:

$$\frac{G_{II}}{G_T} = \frac{G_{II}}{G_I + G_{II}} = \frac{\delta_A^{II} \sigma_0^{II} / 2}{\delta_A^{II} \sigma_0^{II} / 2 + \delta_A^I \sigma_0^I / 2} \tag{D.8}$$

where $\delta_A = \delta_f + \delta_c - \delta_0$, that accounts for the length of the trapeze, while the interlaminar strength $\sigma_0^i = K^i \delta_0^i$ is the height of the trapeze. Then, Eq. (D.9) defines the ratio:

$$\begin{aligned}
 \frac{G_{II}}{G_T} &= \frac{\delta_A^{II} \delta_0^{II} K^I}{\delta_A^{II} \delta_0^{II} K^{II} + \delta_A^I \delta_0^I K^I} = \frac{\beta^2 \delta_A^I \delta_0^I K^I}{\beta^2 \delta_A^I \delta_0^I K^{II} + \delta_A^I \delta_0^I K^I} \Leftrightarrow \\
 &\Leftrightarrow \frac{G_{II}}{G_T} = \frac{\beta^2 K^I}{\beta^2 K^{II} + K^I}
 \end{aligned} \tag{D.9}$$

This only leaves missing the calculation of the Mode specific max displacement of the plateau. For the complete behaviour, the final displacement is directly calculated knowing the area of the triangle in Mode I because and $\delta_c^I(\beta = 0) = \delta_0^I$. This is explicit in the last equation in (D.5). For Mode II, the area of the trapeze is used to attain these displacements, using Eqs. (D.10):

$$\begin{aligned}
 G_{IIc} &= \frac{\delta_f^{II} + \delta_c^{II} - \delta_0^{II}}{2} \sigma_0^{II} \Leftrightarrow \\
 &\Leftrightarrow \frac{2G_{IIc}}{\sigma_0^{II}} + \delta_0^{II} - \left[\frac{2G_{Ic}}{\sigma_0^I} - \frac{\sigma_0^I}{K_I} \right] = 2\delta_c^{II} \Leftrightarrow \\
 &\Leftrightarrow \delta_c^{II}(\beta \rightarrow \infty) = \frac{G_{IIc}}{\sigma_0^{II}} + \frac{\sigma_0^{II}}{2K^{II}} - \frac{G_{Ic}}{\sigma_0^I} + \frac{\sigma_0^I}{2K^I}
 \end{aligned} \tag{D.10}$$

D.1.Fortran Code

```

C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%          VERSION 1.0 GIVEN By F LACHAUD in June 2023          %
C%          Version 2.0 from July 2023 from Rui Gonçalves        %
C%          2D version                                           %
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
C%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

! UMAT (User MATERIAL) custom routine for modelling the mechanical
! behaviour of cohesive elements (CEs) in adhesively bonded joints.

! Hypothesis:
! - Mode II is supposed equal to mode III.

! The implemented CE law formulations in this code are:

! LAW = 1: Trapezoidal damage T-S law (Trapeze).
! LAW = 2: Classical bilinear damage T-S law (Triangle)
! SR = 1: Strain Rate is calculated and used on Stress and ERR
! SR = 2: SR not active
! DISS = 1: Dissipated energy from previous iterations accounted for
different SR
! DISS = 2 DISS not active

C      (energy due to viscous regularization is calculated)
      SUBROUTINE UMAT(STRESS,STATEV,DDSDDE,SSE,SPD,SCD,
1         RPL,DDSDDT,DRPLDE,DRPLDT,
2         STRAN,DSTRAN,TIME,DTIME,TEMP,DTEMP,PREDEF,DPRED,CMNAME,
3         NDI,NSHR,NTENS,NSTATV,PROPS,NPROPS,COORDS,DROT,PNEWDT,
4         CELENT,DFGRD0,DFGRD1,NOEL,NPT,LAYER,KSPT,KSTEP,KINC)

      INCLUDE 'ABA_PARAM.INC'

      CHARACTER*80 CMNAME
      DIMENSION STRESS(NTENS),STATEV(NSTATV),
1         DDSDE(NTENS,NTENS),
2         DDSDDT(NTENS),DRPLDE(NTENS),
3         STRAN(NTENS),DSTRAN(NTENS),TIME(2),PREDEF(1),DPRED(1),
4         PROPS(NPROPS),COORDS(3),DROT(3,3),DFGRD0(3,3),DFGRD1(3,3)

      INTEGER :: i,j,k,LAW,SR,DISS
      REAL*8 ::
STRANT(3),TSTRANT(4),DELTAT_R,G_AREA,G_AREA_OLD,MAXDELTAT,LRATE
      REAL*8 :: CFULL(3,3),CDFULL(3,3),COEF,PI,SR_REF,STRESS_T_OLD,COEF_OLD
      REAL*8 :: KI,KII,KIII,S33,S13,S23,GIC,GIIC,GIIIC,ALPHA,BETA,ETA,DDELTAT
      REAL*8 ::
S330,S130,S230,GIC0,GIIC0,GIIIC0,DELTATOLD,DELTAT_ROLD,GC,GC_OLD
      REAL*8 :: D,DOLD,DV,DVOLD,ZERO, ONE, TWO, HALF,DMAX,DDDE(3)
      REAL*8 :: D0,D01,D02,DC,DC1,DC2,DF1,DF2,DF,DELTAS,DELTAT,DELTAN,CTE
      PARAMETER (ZERO = 0.D0,ONE = 1.D0,TWO = 2.D0, HALF = 0.5D0)

C*****
C      STRANT      STRAIN AT THE END OF THE INCREMENT
C      TSTRANT     TEMPORARY ARRAY TO HOLD THE STRAIN FOR PLANE STRESS PROBLEM
C      CFULL       FULL 6X6 ELASTICITY MATRIX
C      CDFULL.....FULL 6X6 DAMAGED ELASTICITY MATRIX

```

```

C      DERIVATION OF THE DAMAGE VARIABLE ACCORDING TO STRAIN:
C      DDDE      D D/D E
C      STATEV(1)  damage
C      STATEV(2)  damage with viscous regularization
C      STATEV(3)  total displacement ACTING.
C      STATEV(4)  strain rate ACTING.
C      STATEV(5)  GC ACTING

C=====
C=====
C      LAWS AND ACTIVATION OF STRAIN RATE
C=====
C=====
C      LAW   = 1
C      SR    = 2
C      SR_REF = 0.2
C      DISS  = 2

C=====
C      GET THE MATERIAL PROPERTIES ENGINEERING CONSTANTS
C=====

KI = PROPS(1)      !COHESIVE STIFFNESS IN DIRECTION 3 (Mode I)
KII = PROPS(2)     !COHESIVE STIFFNESS IN DIRECTION 1 (Mode II)
KIII = PROPS(3)    !COHESIVE STIFFNESS IN DIRECTION 2 (Mode III)
S330 = PROPS(4)    !CRITICAL OUT OF PLANE NORMAL STRESS
S130 = PROPS(5)    !CRITICAL IN PLANE SHEAR STRESS 1
S230 = PROPS(6)    !CRITICAL IN PLANE SHEAR STRESS 2
GIC0 = PROPS(7)    !CRITICAL ENERGY REALESE RATE IN MODE I
GIIC0 = PROPS(8)   !CRITICAL ENERGY REALESE RATE IN MODE I
GIIIC0 = PROPS(9)  !CRITICAL ENERGY REALESE RATE IN MODE I
ALPHA = PROPS(10)  !EXPOSANT VALUE OF PROPAGATION CRITERION B-K
ETA = PROPS(11)    !VISCOSITY FOR REGULARIZATION with 0.1D0*DTIME
DMAX = PROPS(12)   !MMAX DAMAGE VALUE
LRATE = PROPS(13)  !LOADING RATE, 1 AS REFERENCE IS FOR STATIC,
1E5 for 1m/s for example

C      EXEMPLE PROPERTIES FOR CARBONE-EPOXY LAMINATE FOR DCB TESTS
C      UNIT MPa, N/mm3, N/mm, mm
C=====
C      1      2      3      4      5      6      7      8      9      10      11      12      13
C 30000 30000 30000 xx  xx  xx  xxx  xxx  xxx  xxx 0.00075 0.9999 1
C=====

C=====
C      INITIALISATION / ZEROING
C=====
C      IF (TIME(2) .EQ. 0.) THEN
C          D = ZERO
C          DOLD = ZERO
C          DV = ZERO
C          DVOLD = ZERO
C          DELTAT = ZERO
C          DELTAT_R = ZERO
C          GC = ZERO
C          G_AREA = ZERO
C          DO I=1,NTENS
C              STRANT(I)=ZERO
C          END DO

```

```

      IF (NOEL .EQ. 1) THEN
        WRITE (*,*) 'PROPS', PROPS
        WRITE (*,*) 'LAW', LAW
        WRITE (*,*) 'SR', SR
        WRITE (*,*) 'DISS', DISS
      ENDIF

    ELSE

C=====
C      OLD VALUES LOADING
C=====

      DOLD = STATEV(1)
      DVOLD = STATEV(2)
      DELTATOLD = STATEV(3)
      DELTAT_ROLD = STATEV(4)
      ! GC_OLD = STATEV(5)
      G_AREA_OLD = STATEV(5)
      STRESS_T_OLD = STATEV(6)
      COEF_OLD = STATEV(7)
      MAXDELTAT = STATEV(8)

    ENDIF

C=====
C      CALCULATE THE STRAIN AT THE END OF THE INCREMENT
C=====

      DO I = 1, NTENS
        STRANT(I) = STRAN(I) + DSTRAN(I)
      END DO

C=====
C      COMPUTE DISPLACEMENT ACTING ON ELEMENT
C      COMPUTE MAX STRESS AND ERR ACCORDING TO STRAIN RATE
C=====

      IF (STRANT(1) .GT. 1.D-10) THEN
        IF (NTENS .EQ. 2) THEN
          DELTAT = SQRT(STRANT(1)*STRANT(1)+STRANT(2)*STRANT(2))
          DELTAS = SQRT(STRANT(2)*STRANT(2))
          DELTAN = MAX(STRANT(1), 0.D+00)
          DDELTAT= SQRT(DSTRAN(1)*DSTRAN(1)+DSTRAN(2)*DSTRAN(2))
        ELSE
          DELTAT =
SQRT(STRANT(1)*STRANT(1)+STRANT(2)*STRANT(2)+STRANT(3)*STRANT(3))
          DELTAS = SQRT(STRANT(2)*STRANT(2)+STRANT(3)*STRANT(3))
          DELTAN = MAX(STRANT(1), 0.D+00)
          DDELTAT=
SQRT(DSTRAN(1)*DSTRAN(1)+DSTRAN(2)*DSTRAN(2)+DSTRAN(3)*DSTRAN(3))
        ENDIF

        COEF = DELTAS/STRANT(1) !SQRT(KII/KI) *

      ELSE
        IF (NTENS .EQ. 2) THEN
          DELTAT = SQRT(STRANT(2)*STRANT(2))

```

```

        DELTAS = DELTAT
        DDELTAT= SQRT(DSTRAN(2)*DSTRAN(2))
    ELSE
        DELTAT = SQRT(STRANT(2)*STRANT(2)+STRANT(3)*STRANT(3))
        DELTAS = DELTAT
        DDELTAT= SQRT(DSTRAN(2)*DSTRAN(2)+DSTRAN(3)*DSTRAN(3))
    ENDIF

    COEF = 1.D+20

ENDIF

IF (SR .EQ. 1) THEN

    DELTAT_R = DDELTAT/DTIME
    S33 = S330 + 3.*LOG10(LRATE)
    GIC = GIC0 + 0.1*LOG10(LRATE)
    S13 = S130 + 4.*LOG10(LRATE)
    GIIC = GIIC0 + 0.54*LOG10(LRATE)
    S23 = S230 + 4.*LOG10(LRATE)
    GIIIC = GIIIC0 + 0.54*LOG10(LRATE) !OR DELTAT_R/SR_REF

ELSE

    DELTAT_R = DDELTAT/DTIME
    S33 = S330
    GIC = GIC0
    S13 = S130
    GIIC = GIIC0
    S23 = S230
    GIIIC = GIIIC0

ENDIF

C=====
C          COMPUTE UNDAMAGED STIFFNESS MATRIX
C=====

C    FILL THE NTENS X NTENS FULL STIFFNESS MATRIX
C    Depend on NTENS and if the behaviour, Traction, or traction coupled.

    DO I = 1, NTENS
        DO J = 1, NTENS
            CFULL(I,J)=ZERO
        END DO
    END DO

    CFULL(1,1) = KI
    IF (NTENS .EQ. 2) THEN
        CFULL(2,2) = KII
    ELSE
        CFULL(2,2) = KII
        CFULL(3,3) = KIII
    ENDIF

C=====
C    CASE LAW ONE :  TRAPEZE BEHAVIOUR
C=====

```

```

      IF (LAW .EQ. 1) THEN
C=====
C      COMPUTE CRITICAL DISPLACEMENT FOR EACH MODE
C=====

      D01 = S33/KI
      D02 = S13/KII

      DC1 = D01
      DC2 = GIIC/S13-GIC/S33+S13/(TWO*KII)+S33/(TWO*KI)

      CTE = TWO*GIC/S33 - S33/KI      !Constant DF-DC, using triangle for
mode I
      DF1 = CTE + DC1                !DC1 is equal to D01
      DF2 = CTE + DC2

      IF (STRANT(1) .GT. 1.D-10) THEN
C=====MIXED MODE
      D0 = D01*D02*SQRT((1.+COEF**2.)/((D02*D02)+(COEF**2.)*(D01*D01)))

C=====BENZZEGGAH KENANE Criterion
      DC = (GIC+(GIIC-GIC)*(COEF**2.*KII/(KI+COEF**2.*KII))**abs(ALPHA))/
1      (D0*(KI+(KII-KI)*COEF**2./(COEF**2.+ONE))+D0/TWO+S33/(TWO*KI)-
GIC/S33

      DF = CTE + DC

      ELSE

      D0 = D02
      DC = DC2
      DF = DF2

      ENDIF
C=====
C      COMPUTE DAMAGE
C=====

      IF (D .LE. DMAX) THEN
      IF (DELTAT .GE. D0 .AND. DELTAT .LT. DC ) THEN

      D=ONE-D0/DELTAT

      DO I =1, NTENS
      DDDE(I) = D0*STRANT(I)/(DELTAT*DELTAT*DELTAT)
      END DO

      D = MAX(D,DOLD)

      ELSE IF (DELTAT .GE. DC .AND. DELTAT .LT. DF) THEN

      D = ONE - D0/(DC-DF)*(ONE-DF/DELTAT)

      DO I =1, NTENS
      DDDE(I) = D0*DF*STRANT(I)/(DELTAT*DELTAT*DELTAT*(DF-DC))
      END DO

      D = MAX(D,DOLD)

```

```

        ELSE IF (DELTAT .GE. DF) THEN

            D = ONE

        ELSE
C          DELTAT .LT. D0
            D=DOLD

            DO I =1, NTENS
                DDDE(I) = ZERO
            END DO

        ENDIF

    ELSE

        D = ONE

    ENDIF

C=====
C CASE LAW TWO : TRIANGULAR BEHAVIOUR
C=====
        ELSE IF (LAW .EQ. 2) THEN
C=====
C          COMPUTE CRITICAL DISPLACEMENT FOR EACH MODE AND EQUIVALENT
C=====

            D01 = S33/KI
            D02 = S13/KII

            DC1 = D01
            DC2 = D02

            DF1 = 2.*GIC/S33
            DF2 = 2.*GIIC/S13

            IF (STRANT(1) .GT. 1.D-10) THEN

C=====MIXED MODE
                D0 = D01*D02*SQRT((1.+COEF**2.)/((D02*D02)+(COEF**2.)*(D01*D01)))

C=====BENZZEGGAH KENANE Criterion
                DF = (2.*(GIC+(GIIC-
1              GIC)*(COEF**2.*KII/(KI+COEF**2.*KII))**abs(ALPHA)))/
                (D0*(KI+(KII-KI)*COEF**2./(COEF**2.+ONE)))

            ELSE

                D0 = D02
                DC = DC2      !DC2=D02
                DF = DF2

            ENDIF

C=====
C          COMPUTE DAMAGE
C=====

        IF (D .LE. DMAX) THEN
            IF (DELTAT .GE. D0 .AND. DELTAT .LT. DF ) THEN

```

```

D=DF/ (DF-D0) * (ONE-D0/DELTAT)

DO I =1, NTENS
    DDDE(I) = DF*D0*STRANT(I) / ( (DF-DC) *DELTAT*DELTAT*DELTAT)
END DO

D = MAX(D,DOLD)

ELSE IF (DELTAT .GE. DF) THEN

    D = ONE

ELSE
C    DELTAT .LT. D0
    D=DOLD

    DO I =1, NTENS
        DDDE(I) = ZERO
    END DO

ENDIF

ELSE

    D = ONE

ENDIF

ELSE
    WRITE(*,*) 'Error: LAW MUST BE EQUAL TO 1 OR 2'
    STOP
ENDIF

C=====
C    VISCIOUS EFFECT COMPUTATION
C=====

C    VICOUS EFFECT FOOR FAILURE DAMAGES
    IF (D .GE. DVOLD) THEN
        DV = ETA/(ETA+DTIME)*DVOLD+DTIME/(ETA+DTIME)*D
    ELSE
        DV=DVOLD
    ENDIF

C=====
C    VISCIOUS REGULARIZATION DAMAGED STIFFNES MATRIX COMPUTATION
C=====

    DO I = 1, NTENS
        DO J = 1, NTENS
            CDFULL(I,J) = (1.-DV)*CFULL(I,J)
        END DO
    END DO

C=====
C    NEW STRESSES COMPUTATION
C    CALCULATE G WITH AREA
C=====
C    STRESS(I)=CDFULL(I,I)*STRANT(I)

```

```

STRESS = MATMUL(CDFULL,STRANT)
IF (STRANT(1) .GT. 1.D-10) THEN
  STRESS_T = SQRT(STRESS(1)**2+STRESS(2)**2+STRESS(3)**2)
ELSE
  STRESS_T = SQRT(STRESS(2)**2+STRESS(3)**2)
ENDIF
IF (DELTAT .GT. MAXDELTAT) THEN
  G_AREA = G_AREA_OLD + (DELTAT-
DELTATOLD)*ABS((STRESS_T+STRESS_T_OLD)/2)
ENDIF

C=====
C          JACOBIAN MATRIX UPDATE
C          SIGMA = (1-D)*E.EPSILON = E.EPSILON -D.E.EPSILON
C          DSIGMADEPSILON = DDSDE = E - D.E -E.EPSILON*DDDE
C=====

DDSDDE(1,1) = (CDFULL(1,1)-STRESS(1)*DDDE(1)*(DTIME / (ETA + DTIME)))
DDSDDE(2,2) = (CDFULL(2,2)-STRESS(2)*DDDE(2)*(DTIME / (ETA + DTIME)))
DDSDDE(3,3) = (CDFULL(3,3)-STRESS(3)*DDDE(3)*(DTIME / (ETA + DTIME)))

C=====
C          UPDATE STATE VARIABLES
C=====
! WRITE(*,*) 'CHECKING STATEV-----'
! write(*,*) 'Damage',D
! write(*,*) 'Strain-Rate',DELTAT_R
STATEV(1) = D
STATEV(2) = DV
STATEV(3) = DELTAT
STATEV(4) = DELTAT_R
! STATEV(5) = GC
STATEV(5) = MAX(G_AREA,G_AREA_OLD)
STATEV(6) = STRESS_T
STATEV(7) = COEF**2./(1+COEF**2.)
STATEV(8) = MAX(DELTAT,DELTATOLD,MAXDELTAT)
! WRITE(*,*) 'DDDE(1)',DDDE(1)
! WRITE(*,*) 'DDDE(2)',DDDE(2)
! WRITE(*,*) 'JACOBIAN(1,1)',DDSDDE(1,1)
! WRITE(*,*) 'JACOBIAN(2,2)',DDSDDE(2,2)

IF (TIME(1) .EQ. 0 .AND. NPT .EQ. 1) THEN

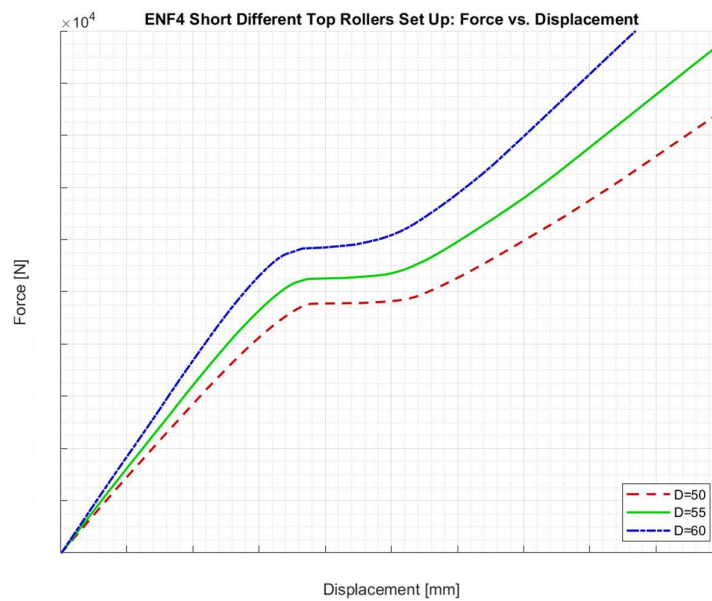
  WRITE(*,*) 'CHECKING OUTPUTS----- AFTER STRAIN RATE'
  WRITE(*,*) 'D0', D0
  WRITE(*,*) 'DC', DC
  WRITE(*,*) 'DF', DF
  WRITE(*,*) 'S33', S33
  WRITE(*,*) 'S13', S13
  WRITE(*,*) 'GIC', GIC
  WRITE(*,*) 'GIIC', GIIC
ENDIF
RETURN
END

C=====
C          END OF MAIN PROGRAM
C=====

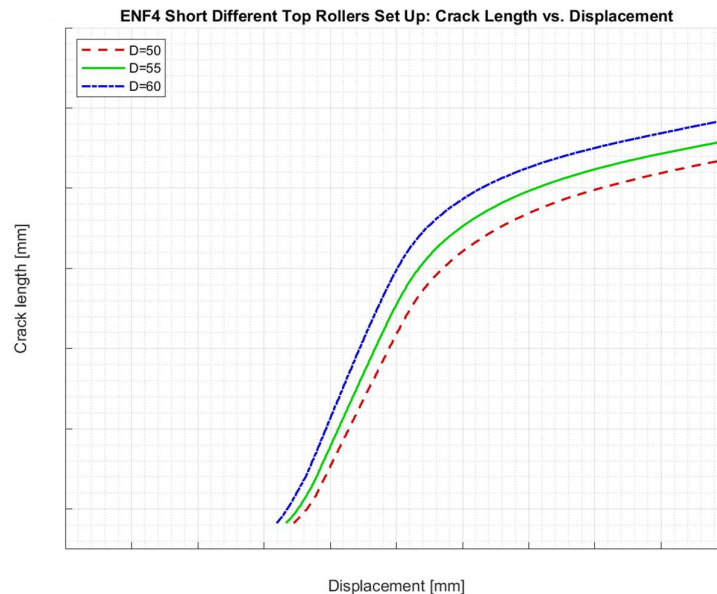
```


Annex E. Short 4ENF loading variance

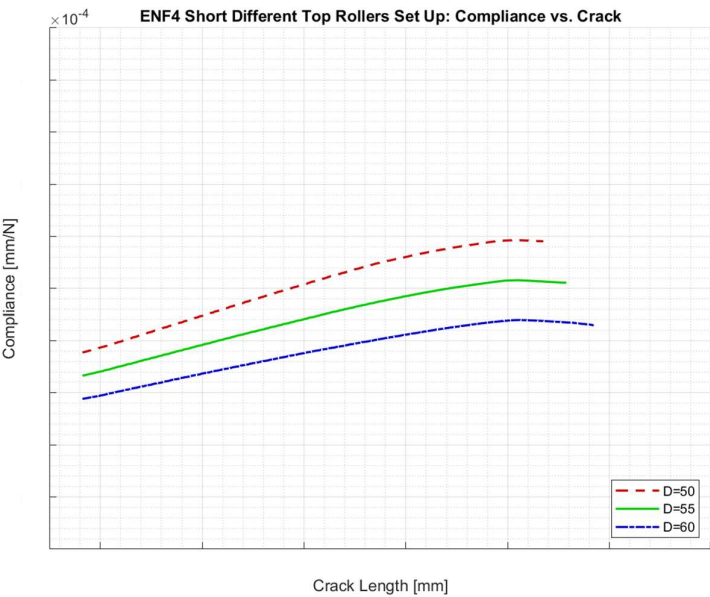
The distance of the top rollers can differ in the experimental test due to the difficult in the set up. To understand if the change in the distance of the rollers would change the DFT calculation, numerical models with cohesive elements without the UMAT based on the short 4ENF specimen were created, where the only difference was the distance between the top rollers. Graph 68, Graph 69, Graph 70 and Graph 71 show the Load vs Displacement results, the Crack Length vs Displacement, the Compliance vs Crack Length and the R-Curve, respectively. Even with the force plateau at a different value, the DFT still tends to the inputted and expected normalised value of $1 \text{ MPa} \cdot \text{mm}$ for every test set up.



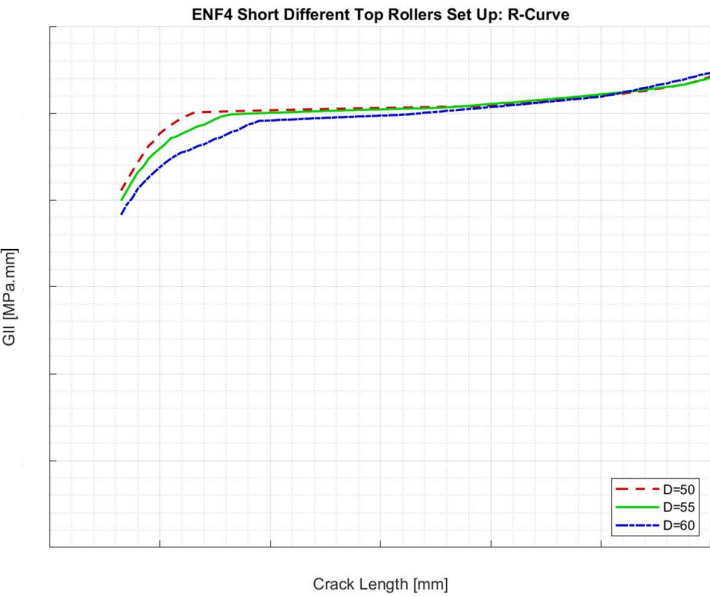
Graph 68 – Short 4ENF with different top rollers set up: Load vs Displacement.



Graph 69 – Short 4ENF with different top rollers set up: Crack Length vs Displacement.



Graph 70 – Short 4ENF with different top rollers set up: Compliance vs Crack Length.



Graph 71 – Short 4ENF with different top rollers set up: R-Curve.

References

- Abrate, S. (2015). "Cohesive zone models and impact damage predictions for composite structures." Meccanica.
- Adachi, T., M. Arai, N. Sakabe and H. Matsumoto (2000). "Evaluation of Dynamic Fracture Toughness of Unidirectional CFRP Laminates." JSME International Journal Series A **43**: 179-185.
- Alan Baker, S. D., Donald Kelly. (2004). Composite materials for aircraft structures. Reston, VA.
- Alderliesten, R. (2018). Introduction to aerospace structures and materials. Delft.
- Alfano, G. (2006). "On the influence of the shape of the interface law on the application of cohesive-zone models." Composites Science and Technology **66**(6): 723-730.
- Althof, W. and G. Neumann (1974). "Verfahren zur Ermittlung von Schubspannungs-Gleitungs-Diagrammen von Konstruktionsklebstoffen in dünnen Klebschichten." **16**(12): 387-388.
- Ansar, M., W. Xinwei and Z. Chouwei (2011). "Modeling strategies of 3D woven composites: A review." Composite Structures **93**(8): 1947-1963.
- Banea, M. and L. F. M. Silva (2009). "Mechanical Characterization of Flexible Adhesives." Journal of Adhesion - J ADHES **85**: 261-285.
- Barenblatt, G. I. (1962). The Mathematical Theory of Equilibrium Cracks in Brittle Fracture. Advances in Applied Mechanics. H. L. Dryden, T. von Kármán, G. Kuerti, F. H. van den Dungen and L. Howarth, Elsevier. **7**: 55-129.
- Benzeggagh, M. L. and M. Kenane (1996). "Measurement of mixed-mode delamination fracture toughness of unidirectional glass/epoxy composites with mixed-mode bending apparatus." Composites Science and Technology **56**(4): 439-449.
- Berger, L. and W. Cantwell (2001). "Temperature and loading rate effects in the Mode II interlaminar fracture behavior of carbon fiber reinforced PEEK." Polymer Composites **22**: 271-281.
- Berger, L. and W. J. Cantwell (2001). "The effect of temperature and loading rate on the mode II interlaminar fracture properties of a carbon fiber reinforced phenolic." Polymer Composites **22**(1): 165-173.
- Blackman, B., A. Kinloch, Y. Wang and J. G. Williams (1996). "The Failure of Fibre Composites and Adhesively Bonded Fibre Composites under High Rates of Test. Part 2." Journal of Materials Science **31**: 4451.
- Blackman, B. R. K., A. J. Brunner and J. G. Williams (2006). "Mode II fracture testing of composites: a new look at an old problem." Engineering Fracture Mechanics **73**(16): 2443-2455.
- Blackman, B. R. K., J. P. Dear, A. J. Kinloch, H. Macgillivray, Y. Wang, J. G. Williams and P. Yayla (1995). "The failure of fibre composites and adhesively bonded fibre composites under high rates of test." Journal of Materials Science **30**(23): 5885-5900.
- Blackman, B. R. K., J. P. Dear, A. J. Kinloch, H. MacGillivray, Y. Wang, J. G. Williams and P. Yayla (1996). "The failure of fibre composites and adhesively bonded fibre composites under high rates of test." Journal of Materials Science **31**(17): 4467-4477.

- Brambleby, R. J., L. A. Louca and S. E. Mouring (2017). "Influence of loading rate on the mode II fracture toughness of vinyl ester GRP." Composites Part A: Applied Science and Manufacturing **93**: 153-162.
- Brunner, A. J., B. R. K. Blackman and P. Davies (2008). "A status report on delamination resistance testing of polymer-matrix composites." Engineering Fracture Mechanics **75**(9): 2779-2794.
- Camanho, P. and C. Dávila (2002). "Mixed-Mode Decohesion Finite Elements for the Simulation of Delamination in Composite Materials."
- Camanho, P. P., C. G. Davila and M. F. de Moura (2003). "Numerical Simulation of Mixed-Mode Progressive Delamination in Composite Materials." Journal of Composite Materials **37**(16): 1415-1438.
- Cantwell, W. J. (1997). "The Influence of Loading Rate on the Mode II Interlaminar Fracture Toughness of Composite Materials." Journal of Composite Materials **31**(14): 1364-1380.
- Carlsson, L., J. Gillespie Jr and B. Pipes (1986). "On the Analysis and Design of the End Notched Flexure (ENF) Specimen for Mode II Testing." J. Compos. Mater. **20**.
- Colin de Verdiere, M., A. A. Skordos, A. C. Walton and M. May (2012). "Influence of loading rate on the delamination response of untufted and tufted carbon epoxy non-crimp fabric composites/Mode II." Engineering Fracture Mechanics **96**: 1-10.
- Compston, P., P. Y. B. Jar, P. J. Burchill and K. Takahashi (2000). The effect of matrix toughness and loading rate on the mode I interlaminar fracture toughness of glass-fibre/vinyl ester composites. European Structural Integrity Society. J. G. Williams and A. Pavan, Elsevier. **27**: 37-48.
- Correlated-Solutions. (2016). Retrieved 15 of May, 2023.
- Daniel, I. M. and O. Ishai (2006). Engineering Mechanics of Composite Materials, Oxford University Press.
- Davies, P., H. H. Kausch, J. G. Williams, A. J. Kinloch, M. N. Charalambides, A. Pavan, D. R. Moore, R. Prediger, I. Robinson, N. Burgoyne, K. Friedrich, H. Wittich, C. A. Rebelo, A. Torres Marques, F. Ramsteiner, B. Melve, M. Fischer, N. Roux, D. Martin, P. Czarnocki, D. Neville, I. Verpoest, B. Goffaux, R. Lee, K. Walls, N. Trigwell, I. K. Partridge, J. Jaussaud, S. Andersen, Y. Giraud, G. Hale and G. McGrath (1992). "Round-robin interlaminar fracture testing of carbon-fibre-reinforced epoxy and PEEK composites." Composites Science and Technology **43**(2): 129-136.
- De Moura, M. F. S. F. (2008). 10 - Interlaminar mode II fracture characterization. Delamination Behaviour of Composites. S. Sridharan, Woodhead Publishing: 310-326.
- de Moura, M. F. S. F. and A. B. de Moraes (2008). "Equivalent crack based analyses of ENF and ELS tests." Engineering Fracture Mechanics **75**(9): 2584-2596.
- Dugdale, D. S. (1960). "Yielding of steel sheets containing slits." Journal of the Mechanics and Physics of Solids **8**(2): 100-104.
- Falk, M., A. Needleman and J. Rice (2001). "A Critical Evaluation of Cohesive Zone Models of Dynamic Fracture." Journal De Physique Iv - J PHYS IV **11**.
- Fan, C., P. Y. Jar and J. J. Cheng (2013). "Internal-Notched Flexure Test for Measurement of Mode II Delamination Resistance of Fibre-Reinforced Polymers." Journal of Composites **2013**: 1-7.
- François BOUSSU, F. C. and M. DECRETTE (2021). "Tissage 3D - Procédé et

produits."

Gerlach, R., C. R. Siviour, J. Wiegand and N. Petrinic (2012). "In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading." Composites Science and Technology **72**(3): 397-411.

Griffith, A. A. (1921). "The Phenomena of Rupture and Flow in Solids." Philosophical Transactions of the Royal Society of London Series A **221**: 163-198.

Guimard, J.-M., O. Allix, N. Pechnik and P. Thévenet (2009). "Characterization and modeling of rate effects in the dynamic propagation of mode-II delamination in composite laminates." International Journal of Fracture **160**(1): 55-71.

Guo, C. and C. T. Sun (1998). "Dynamic Mode-I crack-propagation in a carbon/epoxy composite." Composites Science and Technology **58**(9): 1405-1410.

Hahn, P., H. Channammagari, M. Imbert and M. May (2022). "High-rate mode II fracture toughness testing of polymer matrix composites using the Transverse Crack Tension (TCT) test." Composites Part B: Engineering **233**: 109636.

Hillerborg, A., M. Modéer and P. E. Petersson (1976). "Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements." Cement and Concrete Research **6**(6): 773-781.

Hui, C. Y., A. Jagota, S. Bennison and J. Londono (2003). "Crack blunting and the strength of soft elastic solids." Proceedings of The Royal Society A: Mathematical, Physical and Engineering Sciences **459**: 1489-1516.

Irwin, G. R. (1957). "Analysis of Stresses and Strains Near the End of a Crack Traversing a Plate." Journal of Applied Mechanics **24**: 361-364.

Kageyama, K., I. Kimpara, T. Suzuki, I. Ohsawa, M. Kanai and H. Tsuno (1999). EFFECTS OF TEST CONDITIONS ON MODE II INTERLAMINAR FRACTURE TOUGHNESS OF FOUR-POINT ENF SPECIMENS.

Keshavanarayana, S. and P. Nuggehalli Nandakumar (2009). Rate Sensitivity of Fracture Toughness of Laminated Composites.

Kusaka, T., Y. Yamauchi and T. Kurokawa (1994). "Effects of strain rate on mode II interlaminar fracture toughness in carbon-fibre/epoxy laminated composites." J. Phys. IV France **04**(C8): C8-671-C678-676.

Li, D. and D. Wei (2020) "Rate-Dependent Cohesive Zone Model for Fracture Simulation of Soda-Lime Glass Plate." Materials **13** DOI: 10.3390/ma13030749.

Li, Z., Z. Wang, W. Lu, X. Zhou and T. Suo (2021). "Loading rate dependence of mode II fracture toughness in laminated composites reinforced by carbon nanotube films." Composites Science and Technology **215**: 109005.

Lin, Y. (1988). "Role of matrix resin in delamination onset and growth in composite laminates." Composites Science and Technology **33**(4): 257-277.

Liu, H., H. Nie, C. Zhang and Y. Li (2018). "Loading rate dependency of Mode I interlaminar fracture toughness for unidirectional composite laminates." Composites Science and Technology **167**: 215-223.

Liu, P. F., Z. Gu, X. Q. Peng and J. Zheng (2015). "Finite element analysis of the influence of cohesive law parameters on the multiple delamination behaviors of composites under compression." Composite Structures **131**: 975-986.

- Liu, W. and P. Chen (2019). "A simple procedure for the determination of the cohesive law in 4-ENF test with consideration of the friction and R-curve effect." Engineering Fracture Mechanics **220**: 106651.
- Low, K. O., M. Johar, H. A. Israr, K. W. Gan, S. S. Rahimian Koloor, M. Petrú and K. J. Wong (2021) "Displacement Rate Effects on the Mode II Shear Delamination Behavior of Carbon Fiber/Epoxy Composites." Polymers **13** DOI: 10.3390/polym13111881.
- Ma, L., F. Liu, D. Liu and Y. Liu (2021) "Review of Strain Rate Effects of Fiber-Reinforced Polymer Composites." Polymers **13** DOI: 10.3390/polym13172839.
- Machado, J. J. M., E. A. S. Marques, R. D. S. G. Campilho and L. F. M. da Silva (2017). "Mode II fracture toughness of CFRP as a function of temperature and strain rate." Composites Part B: Engineering **114**: 311-318.
- Magnus, A. K. (2019). Experimental and Numerical Study of Mode II Delamination in Laminated Composite Beams.
- Maikuma, H., J. W. Gillespie and D. J. Wilkins (1990). "Mode II Interlaminar Fracture of the Center Notch Flexural Specimen under Impact Loading." Journal of Composite Materials **24**(2): 124-149.
- Martin, R. H. and B. D. Davidson (1999). "Mode II fracture toughness evaluation using four point bend, end notched flexure test." Plastics, Rubber and Composites **28**(8): 401-406.
- May, M. (2015). "Numerical evaluation of cohesive zone models for modeling impact induced delamination in composite materials." Composite Structures **133**: 16-21.
- Moslemi, M. and M. Khoshnavan (2015). "Cohesive Zone Parameters Selection for Mode-I Prediction of Interfacial Delamination." 2015 **61**(9): 10.
- Mouritz, A. P. (2012). Introduction to aerospace materials. Oxford.
- Ortiz, M. and A. Pandolfi (1999). "Finite-deformation irreversible cohesive elements for three-dimensional crack-propagation analysis." International Journal for Numerical Methods in Engineering **44**(9): 1267-1282.
- Parrinello, F. (2018). Analytical Solution of the 4ENF Test with Interlaminar Frictional Effects and Evaluation of Mode II Delamination Toughness.
- Rezasefat, M., S. C. Amico, M. Giglio and A. Manes (2022) "A Numerical Study on the Influence of Strain Rate in Finite-Discrete Element Simulation of the Perforation Behaviour of Woven Composites." Polymers **14** DOI: 10.3390/polym14204279.
- Ribas, M. J. P., A. Akhavan-Safar, N. Pigray, R. J. C. Carbas, E. A. S. Marques, C. S. P. Borges, S. Wenig and L. F. M. da Silva (2023) "From High Strain Rates to Elevated Temperatures: Investigating Mixed-Mode Fracture Behaviour in a Polyurethane Adhesive." Polymers **15** DOI: 10.3390/polym15122675.
- Rice, J. (1980). "The mechanics of earthquake rupture." **78**.
- Richardson, M. O. W. and M. J. Wisheart (1996). "Review of low-velocity impact properties of composite materials." Composites Part A: Applied Science and Manufacturing **27**(12): 1123-1131.
- Schuecker, C. and B. D. Davidson (2000). "Evaluation of the accuracy of the four-point bend end-notched flexure test for mode II delamination toughness determination." Composites Science and Technology **60**(11): 2137-2146.

- Silva, M. A. L., M. F. S. F. de Moura and J. J. L. Morais (2006). "Numerical analysis of the ENF test for mode II wood fracture." Composites Part A: Applied Science and Manufacturing **37**(9): 1334-1344.
- Smiley, A. J. and R. B. Pipes (1987). "Rate sensitivity of mode II interlaminar fracture toughness in graphite/epoxy and graphite/PEEK composite materials." Composites Science and Technology **29**(1): 1-15.
- Sun, C. T. and C. Han (2004). "A method for testing interlaminar dynamic fracture toughness of polymeric composites." Composites Part B: Engineering **35**(6): 647-655.
- Tabiei, A. and W. Zhang (2018). "Composite Laminate Delamination Simulation and Experiment: A Review of Recent Development." Applied Mechanics Reviews **70**(3).
- Tanaka, K., T. Yuasa and K. Katsura (1998). Continuous mode II interlaminar fracture toughness measurement by over notched flexure test. 4 th European Conference on Composites: Testing and Standardisation.
- Thorsson, S. I., A. M. Waas, J. Schaefer, B. Justusson and S. Liguore (2018). "Effects of elevated loading rates on mode I fracture of composite laminates using a modified wedge-insert fracture method." Composites Science and Technology **156**: 39-47.
- Tran, A. T. (2011). Study of delamination in mode II unidirectional composites subjected to high speed loading : local approach and global approach, Arts et Métiers ParisTech.
- Tsai, J. L., C. Guo and C. T. Sun (2001). "Dynamic delamination fracture toughness in unidirectional polymeric composites." Composites Science and Technology **61**(1): 87-94.
- Turon, A., P. P. Camanho, J. Costa and J. Renart (2010). "Accurate simulation of delamination growth under mixed-mode loading using cohesive elements: Definition of interlaminar strengths and elastic stiffness." Composite Structures **92**(8): 1857-1864.
- Turon, A., C. G. Dávila, P. P. Camanho and J. Costa (2007). "An engineering solution for mesh size effects in the simulation of delamination using cohesive zone models." Engineering Fracture Mechanics **74**(10): 1665-1682.
- Tvergaard, V. and J. W. Hutchinson (1993). "The influence of plasticity on mixed mode interface toughness." Journal of the Mechanics and Physics of Solids **41**(6): 1119-1135.
- van den Bosch, M. J., P. J. G. Schreurs and M. G. D. Geers (2006). "An improved description of the exponential Xu and Needleman cohesive zone law for mixed-mode decohesion." Engineering Fracture Mechanics **73**(9): 1220-1234.
- Volokh, K. Y. (2004). "Comparison between cohesive zone models." Communications in Numerical Methods in Engineering **20**(11): 845-856.
- Wang, W.-X., M. Nakata, Y. Takao and T. Matsubara (2009). "Experimental investigation on test methods for mode II interlaminar fracture testing of carbon fiber reinforced composites." Composites Part A: Applied Science and Manufacturing **40**(9): 1447-1455.
- Wiegand, J., A. Hornig, R. Gerlach, C. Neale, N. Petrinic and W. Hufenbach (2014). "An Experimental Method for Dynamic Delamination Analysis of Composite Materials by Impact Bending." Mechanics of Advanced Materials and Structures **22**.
- Yasaee, M., G. Mohamed, A. Pellegrino, N. Petrinic and S. R. Hallett (2017). "Strain rate dependence of mode II delamination resistance in through thickness reinforced laminated composites." International Journal of Impact Engineering **107**: 1-11.

Zabala, H., L. Aretxabaleta, G. Castillo and J. Aurrekoetxea (2015). "Loading rate dependency on mode I interlaminar fracture toughness of unidirectional and woven carbon fibre epoxy composites." Composite Structures **121**: 75-82.

Zabala, H., L. Aretxabaleta, G. Castillo and J. Aurrekoetxea (2016). "Dynamic 4 ENF test for a strain rate dependent mode II interlaminar fracture toughness characterization of unidirectional carbon fibre epoxy composites." Polymer Testing **55**: 212-218.

Zhang, W. and A. Tabiei (2018). "Improvement of an Exponential Cohesive Zone Model for Fatigue Analysis." Journal of Failure Analysis and Prevention **18**.

Zhao, J., L. Zhang, L. Guo and Y. Yang (2017). "Dynamic properties and strain rate effect of 3D angle-interlock carbon/epoxy woven composites." Journal of Reinforced Plastics and Composites **36**(20): 1531-1541.