Faculdade de Engenharia da Universidade do Porto

Investigating the Dynamic Behaviour of High Performance Fibres

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MSc Thesis

Mestrado Integrado em Engenharia Mecânica

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If I have seen further than others,

it is by standing upon the shoulders of giants.

Isaac Newton

Abstract

The main goal of this thesis is to obtain the dynamic characterization of high performance fibres using a miniaturized Hopkinson bar design in Imperial College London. Beyond the dynamic characterization it was performed quasi-static tests to determine the different behaviours between high and low strain rates. To test the filaments under low strain rates, it was used a Linkam TST350 Tensile Tester and an Instron 5969 while the fibres tested under high strain rate were tested using a miniaturized Hopkinson bar. In order to measure the strain and the strength under high strain rates it was used a high speed camera and a piezoelectric load cell, respectively.

The quasi-static tests performed show that there is a limit of strength for S2-Glass® and Vectran® fibres and that the Weibull analysis cannot be used to predict Vectran® strength. On the other hand Dyneema® SK76 fibres slipped through the glue and for that reason they were not tested dynamically. The dynamic strength of Vectran® and S2-Glass® fibres tested is lower than the quasi-static strength which means there is a strain rate dependence.

Resumo

A presente tese tem como principal objetivo caracterização dinâmica de fibras de alta performance utilizando uma versão miniatura da barra de Hopkinson, desenhada no Imperial College London. Para além da caracterização dinâmica, foram realizados testes quási-estáticos para determinar as diferenças de comportamento entre elevadas e baixas taxas de deformação. As fibras testadas a baixas taxas de deformação foram testadas usando duas máquinas de teste, uma Linkam TST350 e uma Instron 5969, e os testes a elevadas taxas de deformação foram testadas usando uma miniatura da barra de Hopkinson. Para a medição da deformação e da tensão a elevadas taxas de deformação foram usadas, respetivamente, uma câmara de alta velocidade e uma célula de carga, mais propriamente um piezoelétrico.

Os testes quási-estáticos executados demonstram um limite para a tensão das fibras de S2-Glass® e Vectran® e que a análise de Weibull não pode ser usada para prever a tensão de Vectran®. Por sua vez, as fibras de Dyneema® SK76 escorregaram através da cola e por essa razão não foram testadas dinamicamente. A tensão dinâmica das fibras de Vectran® e S2-Glass® testadas é inferior à tensão quási-estática, o que significa que a tensão depende da velocidade da taxa de deformação.

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I want to express my gratitude to my friends. In their one way, they helped me achieving my goals. They never let me down and I will be forever thankful to them. In moments of choices they don't allow me to do bad ones. Every time that I need something they were there to help me.

Lastly, I would like to thank my mother, Maria Correia. I am what I am because she taught me this way, at her own image. She never gave up on me and she gave me everything she could. She told that if I give always my best I can be succeed. I would like to thank my father, Fernando Costa. Usually we think that we can't make an omelette without breaking eggs, but he taught exactly the opposite: there is always a way to do something. It may look impossible but if we work hard it will be the easiest thing ever. Finally, I would like to thank my entire family.

Contents

Acronyms and Abbreviations

HSR	High Strain Rate
MSHPB	Mini Split Hopkinson Pressure Bar
N.A.	Not Available
SHPB	Split Hopkinson Pressure Bar
QS	Quasi-static
UHMW	Ultra Height Molecular Weight

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1 Literature review

1.1 Introduction

Most of the mechanical properties of materials are obtained under quasi-static loading conditions, but not always the structures are exposed to this type loading. The dynamic characterization of materials should be studied because the behaviour of materials may be different from quasi-static loading conditions. In this thesis it will be studied the dependence of the single fibres on strain rate, testing Vectran®, Dyneema® and S2-Glass® fibres under quasi-static and high strain rate.

Some materials present strain rate dependence which means they don't exhibit the same behaviour under quasi-static and high strain rate. This behaviour becomes important if the materials are exposed to a different loading conditions than the mechanical properties were obtained. Composite materials are being used in aircraft structures due to their low weight but their use requires a perfect understanding of their behaviour.

The mechanical properties of single fibres under high strain rates are difficult to achieve due to the small size of the specimens. Before the failure of the fibre there must be a state of equilibrium and ensure that the filament don't slip during the procedure. In order to avoid the slipping of the fibre, it can be used glue or a clamping system but this way there will be stress concentrations.

1.2 Split Hopkinson Pressure Bar

The Split Hopkinson Pressure Bar (SHPB), also known as the Kolsky bar, is used to determine the mechanical properties of materials under high strain rates and Hopkinson bar experiments can reach strain rates between 10^2 to $10^4\ s^{-1}$.

The Hopkinson bar consists of two bars, the incident (or input) bar and the transmission (or output) bar, in which between them there is a sample of the material to be studied. A striker usually accelerated by a gas gun hits the incident bar causing an elastic wave pulse. When this wave reaches the end of the incident bar, a part of it will be reflected and the rest will pass through the sample. This reflection is due to the difference of impedance between the sample and the input bar.

Frequently, to measure the strain, it is used strain gauges attached to both bars to measure the reflected and the transmitted wave although it can be used high speed cameras triggered manually or by the signal from the strain gauges. [3, 4]

The reliability of the mechanical properties obtained using the Hopkinson bar test is achieved if, during the failure of the specimen, the specimen is in a state of dynamic equilibrium and the strain rate is constant.

1.3 Miniaturized Hopkinson Bar

Single fibre experiments require a small load (less than 2N), due to the sample size. Since the load is small, it leads to a new version of the Hopkinson bar. Usually the diameter of the bars are smaller (the lower setup is due to the need of smaller load) but there are some other variations, such as replacing the transmission bar with a piezoelectric load cell. This last version uses the piezoelectric load cell to measure the stress and will be the approach used on this thesis for dynamic experiments.

Lim et al. [8] designed a miniaturized Hopkinson bar to test PPTA single fibres. The authors replaced the output bar with a piezoelectric load cell. To produce the wave, they used a striker, launched by a spring system into a flange where this flange was part of the incident bar. The striker was separated from the incident bar by a brass tube, minimizing noise during the reading. In order to obtain a constant amplitude pulse and a constant strain rate during the experiment, the authors used a pulse shaper placed in the flange. The sample was glued between two small plates at the end of the input bar and the end of the load cell. [7, 8, 9]

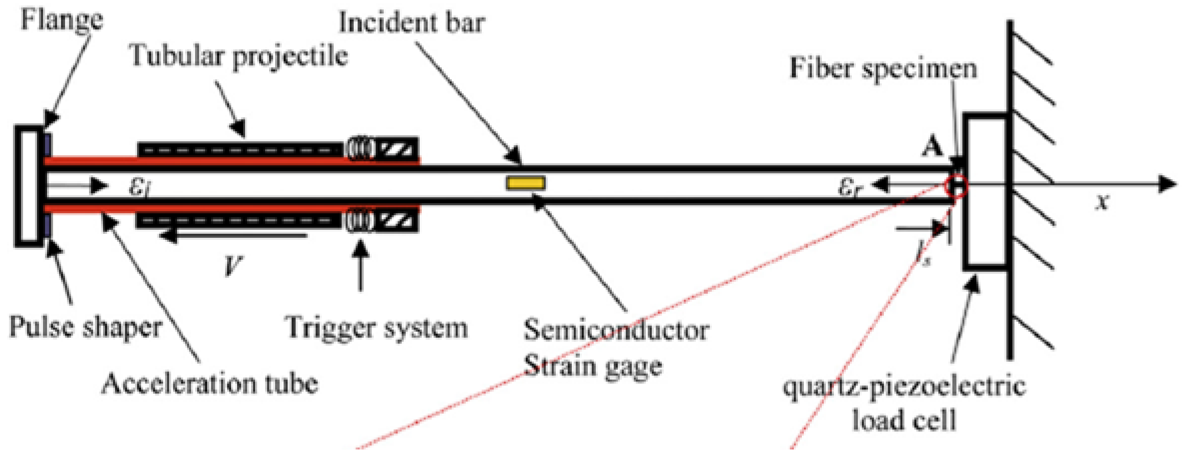

Figure 1 - Miniaturized Hopkinson bar with a piezoelectric load cell. [8]

1.4 High performance fibres

The fibres used in the experiments made by Huang et al. [25] were produced by DSM and tested in a bar-bar tensile impact apparatus. This setup consists in a short metal bar connected to a block and to an input bar. When the hammer hits the block, the block will deform and break the short bar producing a stress impulse as in the Hopkinson bar experiment. These experiments were conducted at two different temperatures and the table shows the dependence of the mechanical properties on the temperature.

Benloulo et al. [26] characterized the dynamic properties of woven fabric of polyethylene and unidirectional composite of polyethylene. The specimens produced from the previous materials were glued to the bars (the authors used the Hopkinson bar experiment) to avoid the use of a clamping system. However, the specimens slipped, and the authors had to design a clamping system without changing the wave propagation.

Languerand et al. [32] analysed the tensile behaviour and fracture mechanisms. The difference between the two samples used during the experiments, beyond the crystalline order, was the difference between the number of filaments in each specimen: HPME-A fibre bundles had 120 filaments (38 μm of diameter for single fibre) and of HPME-B fibre bundles had 240 filaments (26 μm of diameter for single fibre). The authors used a laser detector to measure the initial fibre bundle length and the fibre bundle elongation.

Justo [19] characterized Dyneema® SK66, testing the samples using the Hopkinson bar. For the dynamic tests, Justo used four different specimens: type 3 specimen with 5 layers, type 3 specimen with 2 layers, type 4 specimen with 5 layers and type 4 specimen with 2 layers. In both cases, the type 3 and type 4 specimens had the same gauge length, 20 mm. However, the width was different: type 3 had 12 mm and type 4 had 10 mm. The 5 layers specimen was tested at 200 s^{-1} strain rate and under quasi-static loading conditions: the ultimate strength increase by 37% and the strain failure decrease by 29%. The 2 layers specimen was tested at 135 s^{-1} and under quasi-static loading conditions: the ultimate strength increase by 13%.

Adrian [31] studied the dynamic behaviour of Spectra® 900 and Spectra Shield® LCR. The author developed a clamping system to hold the specimens. The specimens of Spectra® 900, before the tests were heated for 30 minutes in a chamber placed at the end of the input bar and the beginning of the output bar. The Spectra Shield® LCR consists of two plies of unidirectional Spectra® 1000 extended-chain laid perpendicular to each other, and sandwiched between two thermoplastic films.

Koh et al. [34] developed an algorithm to obtain correct results, due to the grips that introduced an impedance mismatch with the input/output bars.

Table 1 - Mechanical properties of Polyethylene fibres

Fiber	Specimen	Linear density (dtex)	Strain Rate (1/s)	Ultimate Strength		Failure Strain		Young's		Gauge Length (mm)	Reference
				GPa	% (vs QS)	-	% (vs QS)	GPa	% (vs QS)		
SK66	Yarns	N.A.	0.001	0.405	-	0.102	-	-	-	30	[26]
			1	0.46	13.6	0.064	-37.3	-	-		
			1000	0.631	55.8	0.025	-75.5	-	-		
UD66			0.001	-	-	-	-	-	-		
			1	0.372	-	0.053	-	-	-		
			1000	0.654	75.8	0.016	-69.8	-	-		
PET1		3360	0.001	0.27	-	0.05	-	-	-		
			1	0.32	18.5	0.05	0.0	-	-		
			1000	0.411	52.2	0.011	-78.0	-	-		
PET2			0.001	0.359	-	0.059	-	-	-		
			1	0.445	24.0	0.06	1.7	-	-		
			1000	0.51	42.1	0.029	-50.8	-	-		
UHMWPE fibres	Fibre Bundles	N.A.	300 (25 °C)	2.55	-	0.0652	-	80	-	8	[25]
			300 (70 °C)	2.47	-	0.0754	-	61	-		
			700 (25°C)	2.55	-	0.0626	-	82	-		
			700 (70°C)	2.48	-	0.0657	-	68	-		
HPME-A	Fibre Bundles	N.A.	Quasi-static	2.40	-	0.0410	-	66	-	3.416 to 4.539	[32]
			340	0.96	-60.0	0.1400	241.5	25	-62.1		
			530	0.80	-66.7	0.1240	202.4	40	-39.4		
			800	1.07	-55.4	0.1940	373.2	19	-71.2		
HPME-B			Quasi-static	3.25	-	0.0290	-	113	-		
			540	1.82	-44.0	0.1930	565.5	33	-70.8		
			670	2.03	-37.5	0.1940	569.0	36	-68.1		
Spectra 900	Yarns	1333	0.001 (20	1.641	-	0.052	-	-	-	25	[31]
			433 (20°C)	2.519	53.5	0.029	-44.2	-	-		
			0.001 (40	1.574	-	0.067	-	-	-		
			477 (40°C)	2.46	56.3	0.04	-40.3	-	-		
			0.001 (60	1.334	-	0.076	-	-	-		
			510 (60°C)	2.463	84.6	0.038	-50.0	-	-		
Spectra Shield		N.A.	0.002 (20	0.2458	-	0.048	-	-	-		
			465 (20°C)	0.7492	204.8	0.031	-35.4	-	-		
Spectra Shield	Yarns	N.A.	0.001	1.5	-	0.05	-	-	-	25	[34]
			365-433	2.5	66.7	0.029	-42.0	-	-		

Error! Reference source not found. shows, the strain rate affects the mechanical properties of the aramid fibres. All the fibres present a significant change comparing quasi-static and dynamic experiments, except the experiments made by Dooraki et al [33]. For the same fibre, Kevlar® 49, there are two different behaviours: the tests performed by Wang et al. [27] shows an increasing ultimate strength with increasing strain rate, while the tests performed by Languerand et al. [32] the opposite behaviour occurred.

Table 2 - Mechanical properties of Aramid fibres

Fiber	Specimen	Linear density (dtex)	Strain Rate (1/s)	Ultimate Strength GPa	Ultimate Strength % (vs QS)	Failure Strain -	Failure Strain % (vs QS)	Young's GPa	Young's % (vs QS)	Gauge Length (mm)	Reference
Kevlar 129 (1154 fibres)	Fibre Bundles	940	Quasi-static	2.85	-	-	-	-	-	8	[33]
			Dynamic	2.9	1.8	-	-	-	-		
Kevlar KM2 (1166 fibres)		950	Quasi-static	2.87	-	-	-	-	-		
			Dynamic	3.08	7.3	-	-	-	-		
Kevlar LT (1080 fibres)		440	Quasi-static	2.75	-	-	-	-	-		
			Dynamic	2.78	1.1	-	-	-	-		
Twaron (1350 fibres)		1100	Quasi-static	2.66	-	-	-	-	-		
			Dynamic	3.27	22.9	-	-	-	-		
Kevlar 49	Fibre Bundles	1270	0.0001	2.34	-	0.0329	-	97	-	8	[27]
			0.01	2.47	5.6	0.0333	1.2	100	3.1		
			140	2.94	25.6	0.0354	7.6	112	15.5		
			440	3.02	27.5	0.0364	10.5	119	22.0		
			1350	3.08	25.2	0.0386	16.1	125	25.0		
PPTA-A (Kevlar 49)	fibre bundles	N.A.	Quasi-static	3.4	-	0.0310	-	77	-	3.416 to 4.539	[32]
			500	1.57	-53.8	0.0500	61.3	59	-23.4		
			850	1.89	-44.4	0.0950	206.5	48	-37.7		
PPTA-B (Kevlar 29)			Quasi-static	3.0	-	0.0370	-	63	-		
			560	2.9	-3.3	0.1000	170.3	41	-34.9		
			580	2.4	-20.0	0.1060	186.5	41	-34.9		
PPTA-C			Quasi-static	3.1	-	0.0240	-	120	-		
			500	3.8	22.6	0.1000	316.7	99	-17.5		
			540	3	-3.2	0.1000	316.7	105	-12.5		

Lim et al. [8] used a modified Hopkinson bar to performed their experiments. The authors used a miniaturized Hopkinson bar, replacing the transmission bar with a piezoelectric load cell. The incident bar had 6.35 mm of diameter and 1651 mm length, made of aluminium. They tested five different gauges length, 2.5, 5.5, 10, 50, 100 and 250 mm, and removed the Kevlar fibres from woven fabric, in warp and weft directions, and from a yarn that not suffered a weaving process. The high strain rates experiments were performed at 1500 s^{-1}, and, to achieve a constant-amplitude incident pulse, the authors used a pulse shaper. From the results, the research team concluded that the fibres studied did not show a significant strain rate or gauge length dependence.

Table 3 - Mechanical properties of other fibres

Fiber	Specimen	Linear density (dtex)	Strain Rate (1/s)	Ultimate Strength		Failure Strain		Young's		Gauge Length (mm)	Reference
				GPa	% (vs QS)	-	% (vs QS)	GPa	% (vs QS)		
Zylon (1268 fibres)	Fibre Bundles	560	Quasi-static	4.12	-	-	-	-	-	8	[33]
			Dynamic	6.55	59.0	-	-	-	-		
PP	Yarns	3360	0.001	0.503	-	0.068	-	-	-	30	[26]
			1	0.533	6.0	0.069	1.5	-	-		
			1000	0.575	14.3	0.039	-42.6	-	-		

Dooraki [33] performed high strain rates tests on aramid fibres in a miniaturized Hopkinson bar. He used a high speed camera to measure the deformation of the specimens during the experiments. The average strain rate was calculated by averaging the displacement rate obtained from each frame.

In order to measure the effect of specimen size on failure stress, Dooraki [33] tested single fibres and multi-fibre specimens of Kevlar® 129 with various gauge lengths(5, 16, 25, 50 and 100 mm, for the single fibre experiments, and 24, 100 and 170 mm for the multi-fibre experiments), but the author only tested the specimens under quasi-static loading conditions. However, it can be seen a significant dependence of Failure Stress with increasing gauge length: the higher gauge length, the lower failure stress was found, although this effect is more evident for multi-fibre. Another effect was perceptible: for the same gauge length, there were two different specimens, one with 1154 fibres and other with 2308 fibres. The specimen with more fibres had a lower failure stress, and this effect can be explain due to the friction between the fibres. Hill and Okoroafor [36] performed tests on fibre bundles to obtained tensile properties of fibres, and they used fibre bundles lubricated and fibre bundles without any lubrication. The authors concluded that the lubrication does not affect the Young's Modulus, however, the ultimate strength and the failure strain are significantly reduced in the dry bundle tests.

1.5 Problems characterizing fibre bundles

In order to measure the mechanical properties of fibres, in this thesis, it was used single fibres, although it could be used fibre bundles. Measuring mechanical properties using single fibres can introduce errors due to fibre damage during the preparation of the samples, but on the other hand using fibre bundles can minimize this problem.

It is expected that different methods leads to different results. Hill and Okoroafor [36] performed tests using lubricated and non-lubricated fibre bundles at low strain rates, and tried to explain the difference between the results obtained. One of the main reasons can be explained due to interfibre interaction/friction during the experiment. The authors concluded that the lubrication does not affect the Young's Modulus of the fibres, however the Ultimate Strength and the Failure Strain are significantly affected by lubrication. The lubricated fibre bundles had higher Ultimate Strength and Failure Strain values.

2 Quasi-Static Experiments

2.1 Fibre preparation

In order to perform the quasi-static tests, it was need to prepare the samples to be tested. The single fibres were placed in a frame template printed out on card (if the paper is not strong enough, the fibre can be damage during the preparation and handling). In the template there is double-sided tape to align and hold the fibres before glue them with an appropriate glue.

The gauge length is set by the window cut in the template. For the experiments the gauge lengths tested on the Linkam TST350 were 15, 20 and 25 mm (the Tensile Stress Tester only allow at least 14 mm) and on the Instron 5969, the gauge lengths tested were 4, 6 and 8 mm. To test the single filaments using the Instron 5969, it was need to develop a clamping system. The clamping system (**Error! Reference source not found.**) consists in two aluminium parts and two screws to tight the template and avoid any slippage. On the other end of the template there is a pneumatic grip.

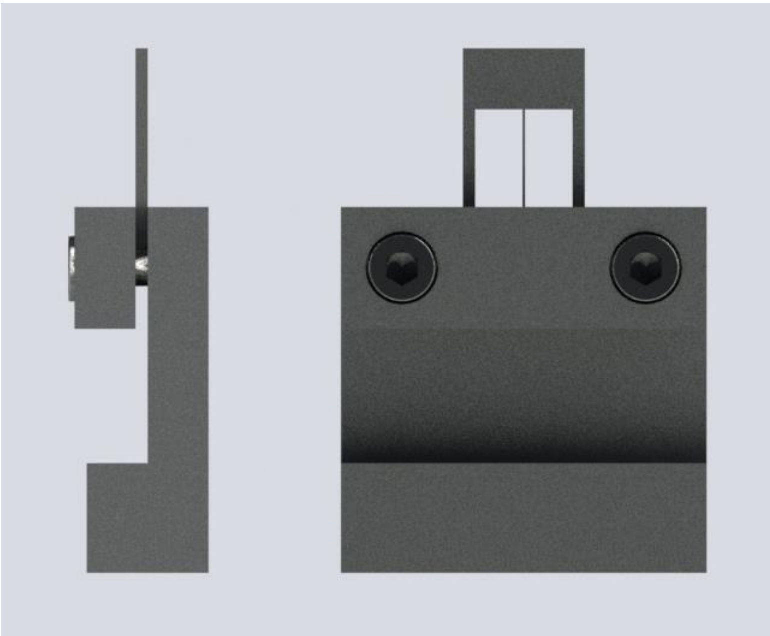

Figure 2 - Clamping system used on the Instron 5969 Tensile Tester

The glue used to glue the fibres was Araldite Rapid, an epoxy glue. It should not be used super glue unless a standard explicitly says to use it. Although the ultimate strength is the same if it is used super glue or epoxy glue, the Young's Modulus will be affected by the super glue. A complete cure of the epoxy glue used should last at least 3 nights. After the cure, the double-tape attached to the template is cut off and the samples are ready to be tested. Figure 3 shows the frame template after the preparation.

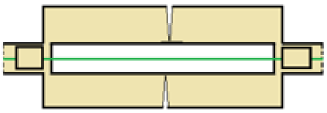

Figure 3 - Frame Template

2.2 Quasi-static tests

The quasi-static tests were performed using a Linkam TST350 Tensile Stress Tester, with a 20N load cell and an Instron 5969 with a 10N load cell. The frame template is clamped and aligned before the test start. After clamping the frame, the card that keep the fibre stretched (Figure 3) should be cut, otherwise the fibre won't be properly tested. A previous pre-cut before glue the fibre to the frame template will allow an easier cur and avoid any damage on the fibre.

Before perform the test the force and displacement were set to zero (both software, Linkam and Instron, had an option to set these values to zero). The strain rate was set to 0.001/s, the lowest strain rate that the Linkam Tensile Stress Tester could achieve, even though the Instron could achieve lower strain rates.

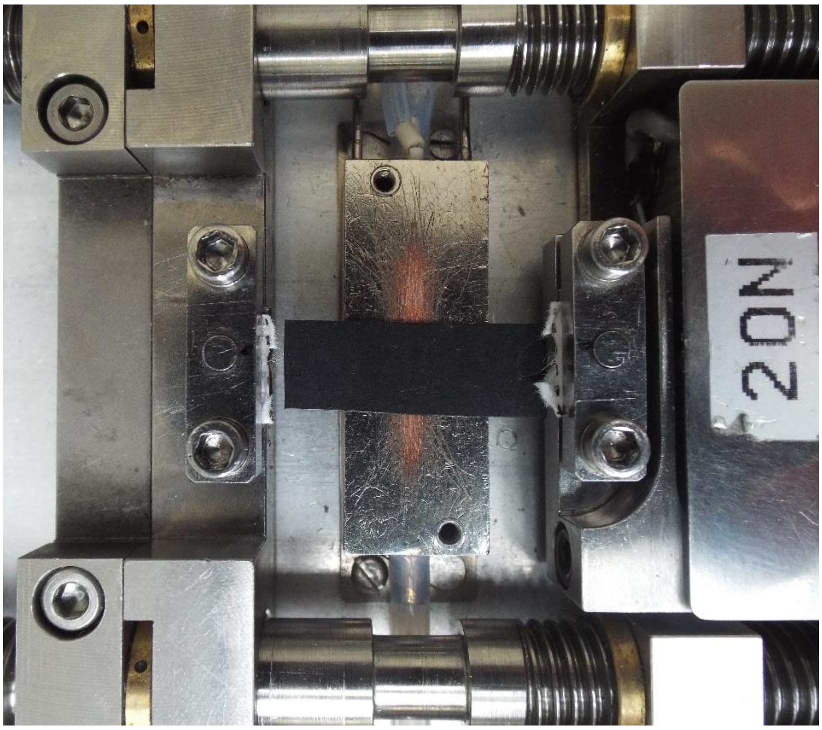

Figure 4 - Linkam TST350 Tensile Tester

For each gauge length were tested 30 samples. However not all of them were considered to obtain the mechanical properties, because in some of the tests the fibre slipped through the glue and on others tests there were more than one filament being tested. Nevertheless from the 30 samples prepared for each gauge length, at least 15 were used to obtain the final results. The Araldite Rapid glue, an epoxy glue, was able to glue Vectran® and S2-Glass® fibres properly, however Dyneema® SK76 fibres seemed to slip through the epoxy glue. Dyneema® SK76 filaments slipped through the glue because they are made of polyethylene and the epoxy glue used was not able to glue this material. To glue the filaments of Dyneema® SK76 it was used a cyanoacrylate glue, Loctite® 401. However, although the fibre didn't slipped, the strain and consequently the modulus were too different from the literature which could be caused by micro-slippage of the filaments through the glue. It was found out that Dyneema® fibres require a primer before glue them with a low viscosity cyanoacrylate glue. Nonetheless, it was impossible to test Dyneema® SK76 filaments using a primer plus a low viscosity cyanoacrylate glue because the fibres continued to slip.

2.3 Results and Discussion

The fibres were tested at room temperature and the materials were tested on the same day, to avoid any changes of temperature and humidity. **Error! Reference source not found.** shows the mechanical properties of Vectran®, S2-Glass® and Dyneema® SK76 single fibres under quasi-static loading conditions. It was tested three different gauge length to obtain the compliance of the tensile testers used. The Modulus and the strain to failure are after system compliance. The sampling rate was 3.33 samples per second for the Linkam and 10 samples per second for the Instron.

Table 4 - Mechanical properties

Tensile Tester	Material	Radius [m]	Gauge Length [mm]	Strain Rate [1/s]	Ultimate Strength [MPa]		Corrected Failure Strain		Modulus [GPa]	Number Valid Tests
					Average	Standard Deviation	Average	Standard Deviation	Average	
Linkam TST350	Vectran	1.088E-05	15	0.001	3623	408	0.0247	0.0038	86	16
Linkam TST350	Vectran	1.088E-05	25	0.001	3918	255	0.0307	0.0031	92	17
Linkam TST350	Vectran	1.088E-05	35	0.001	3816	297	0.0270	0.0022	110	19
Instron 5969	Vectran	1.088E-05	4	0.001	3937	413	0.0449	0.0141	88	16
Instron 5969	Vectran	1.088E-05	6	0.001	3593	304	0.0392	0.0171	92	18
Instron 5969	Vectran	1.088E-05	8	0.001	3882	350	0.0454	0.0071	86	23
Linkam TST350	S2-Glass	3.729E-06	15	0.001	3916	376	0.0564	0.0052	69	17
Linkam TST350	S2-Glass	3.729E-06	25	0.001	2901	459	0.0377	0.0055	77	15
Linkam TST350	S2-Glass	3.729E-06	35	0.001	2367	429	0.0287	0.0063	82	17
Instron 5969	S2-Glass	3.729E-06	4	0.001	3550	348	0.0561	0.0093	63	14
Instron 5969	S2-Glass	3.729E-06	6	0.001	3906	342	0.0554	0.0095	70	15
Instron 5969	S2-Glass	3.729E-06	8	0.001	3884	600	0.0599	0.0105	65	16
Linkam TST350	Dyneema SK76	9.154E-06	15	0.001	2822	223	0.0461	0.0094	61	18
Linkam TST350	Dyneema SK76	9.154E-06	20	0.00075	2886	245	0.0425	0.0076	68	21
Linkam TST350	Dyneema SK76	9.154E-06	25	0.0006	2948	265	0.0472	0.0059	62	16
Linkam TST350	Vectran	1.088E-05	20	0.00075	3558	383	0.0385	0.0036	92	22
Linkam TST350	Vectran	1.088E-05	25	0.0006	3713	312	0.0427	0.0061	87	19
Linkam TST350	S2-Glass	3.729E-06	20	0.00075	3793	498	0.0513	0.0062	74	15
Linkam TST350	S2-Glass	3.729E-06	25	0.0006	3425	413	0.0494	0.0072	69	21

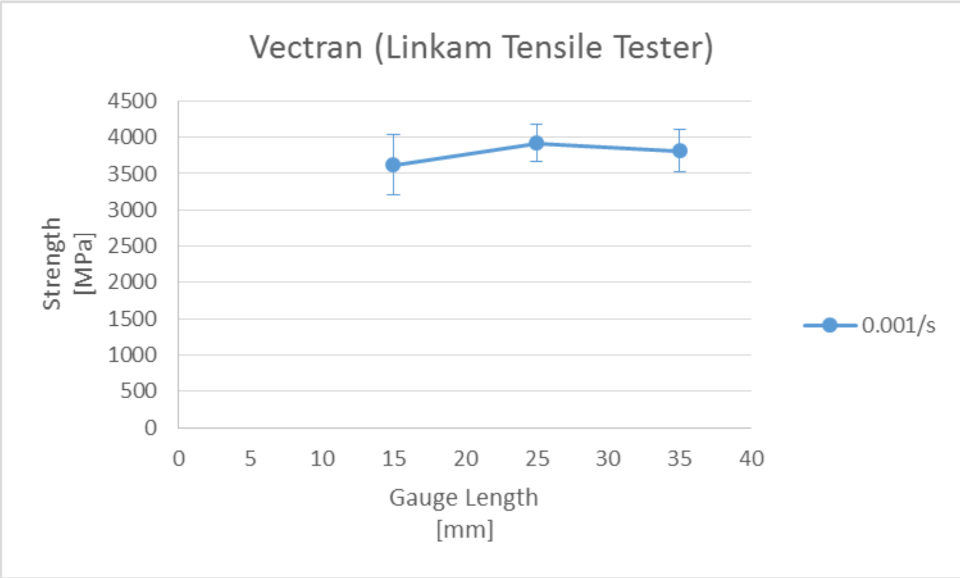

Figure 5 - Tensile strength of Vectran® single fibres (Linkam Tensile Tester)

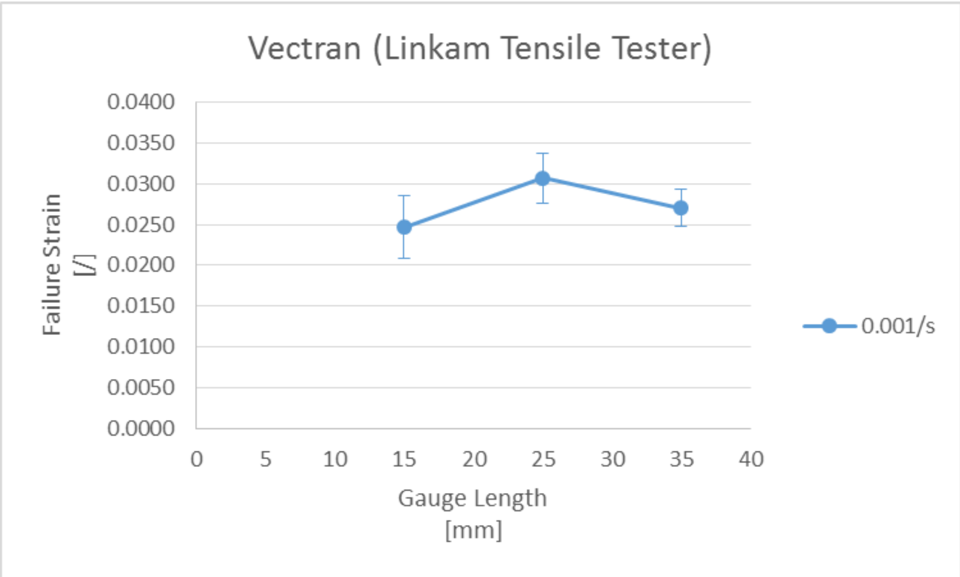

Figure 6 - Corrected Strain at failure of Vectran® single fibres (Linkam Tensile Tester)

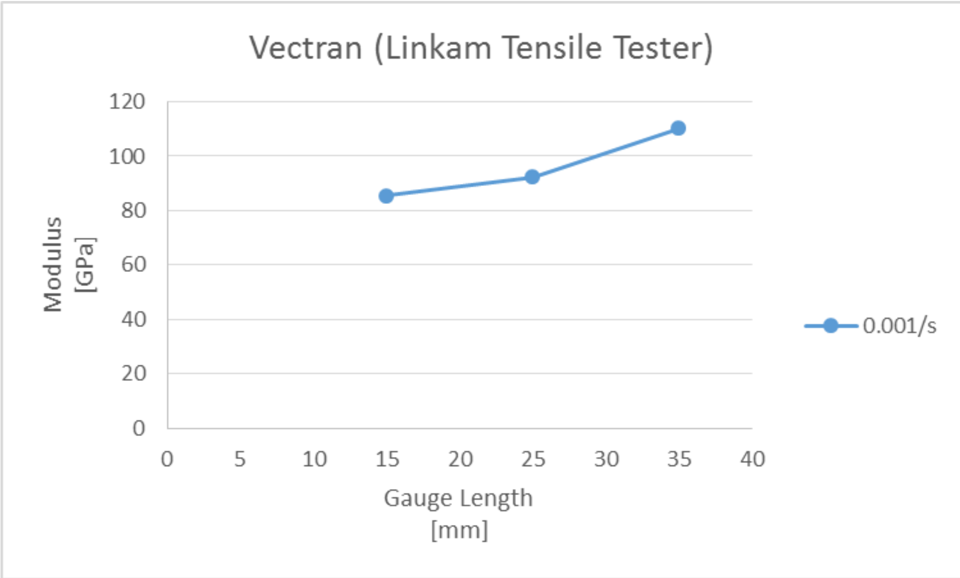

Figure 7 - Corrected Young's Modulus of Vectran® single fibres (Linkam Tensile Tester)

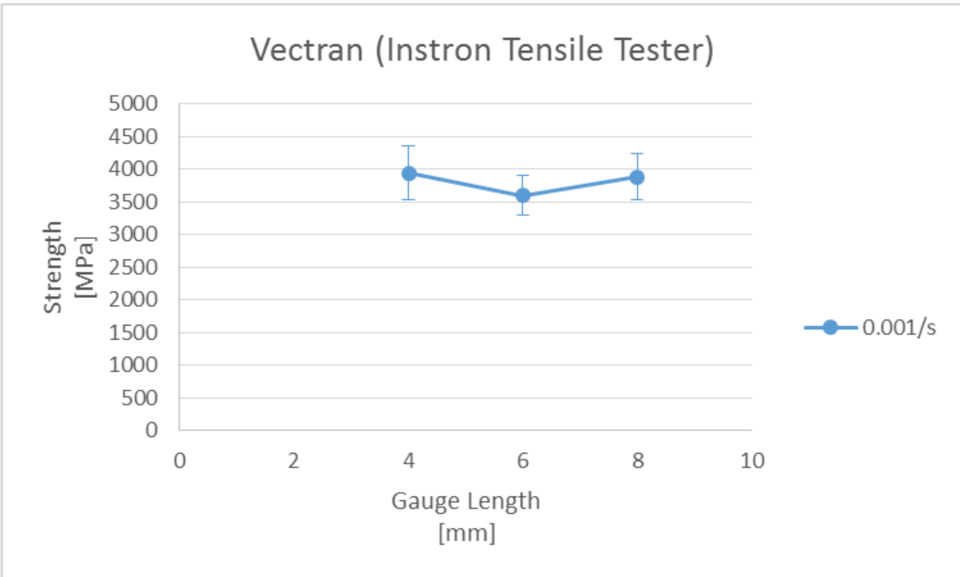

Figure 8 - Tensile strength of Vectran® single fibres (Instron Tensile Tester)

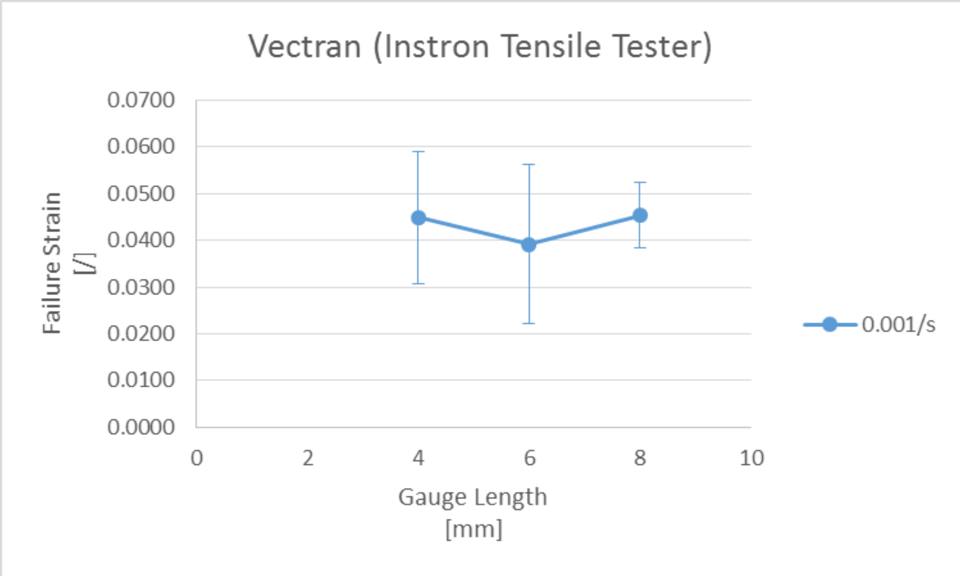

Figure 9 - Corrected Strain at failure of Vectran® single fibres (Instron Tensile Tester)

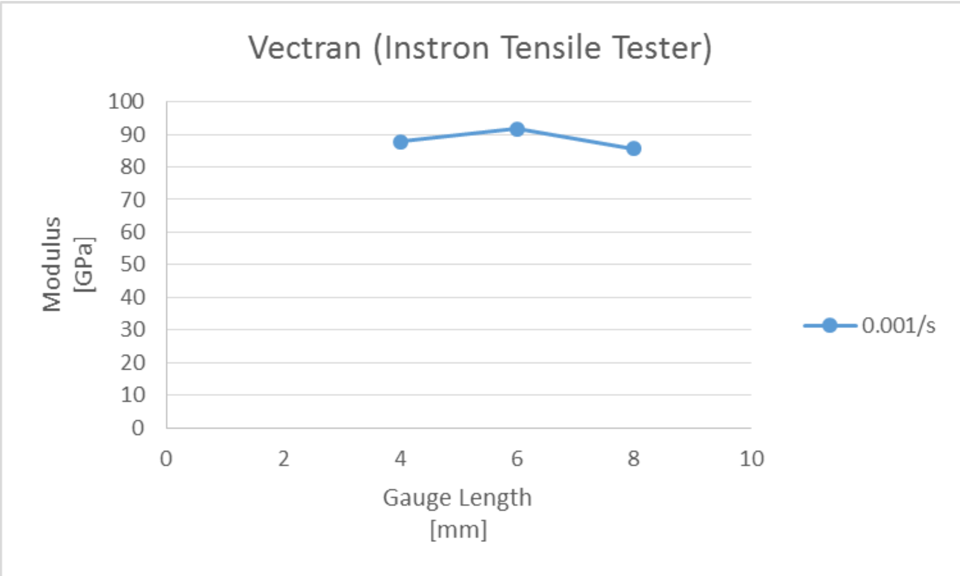

Figure 10 - Corrected Young's Modulus of Vectran® single fibres (Instron Tensile Tester)

The strength of Vectran® fibres tested using the Linkam Tensile Tester don't exhibit a gauge length dependence, which means the Weibull analysis cannot be used. This is why it was needed to test Vectran® at lower gauge length than 15 mm. To compare the mechanical properties under quasi-static and high strain rates, the gauge length should be the same. shows the strength obtained using the Instron 5969 tensile tester and the prediction obtained using the Weibull distribution.

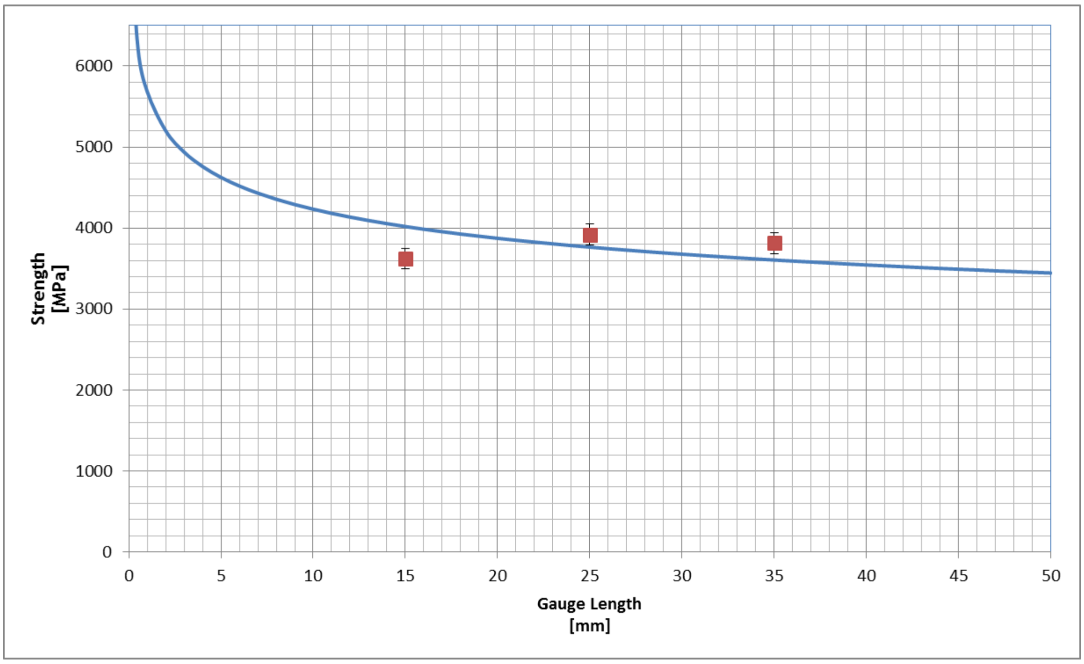

Figure 11 - Weibull analysis for Vectran®

Table 5 - Experimental and prediction of Vectran® fibres strength

Gauge length [mm]	Strength [MPa]	
	Weibull Analysis	Experimental
4	4761	3937
6	4520	3593
8	4356	3882

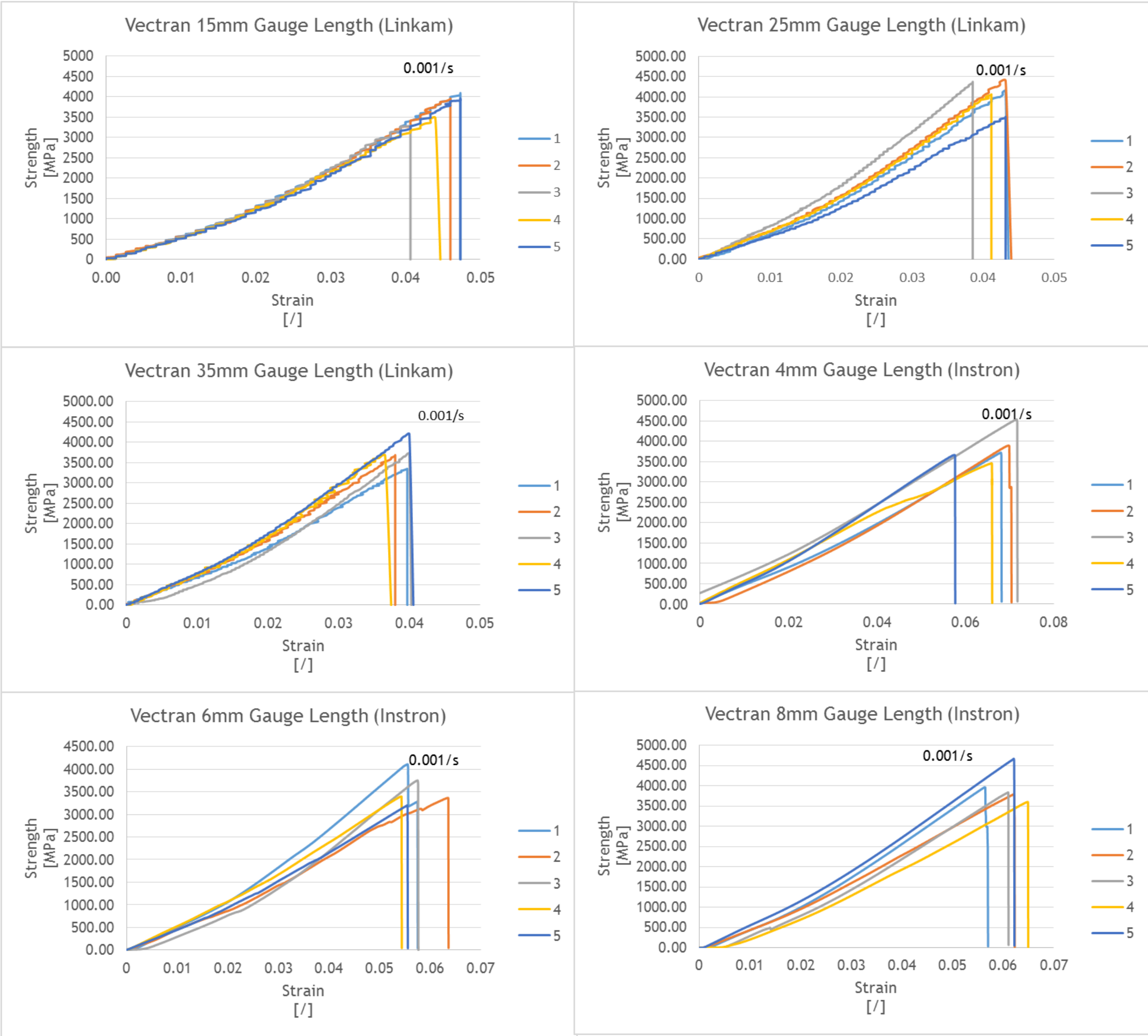

Figure 12 - Typical Stress vs Strain curves (before system compliance correction)

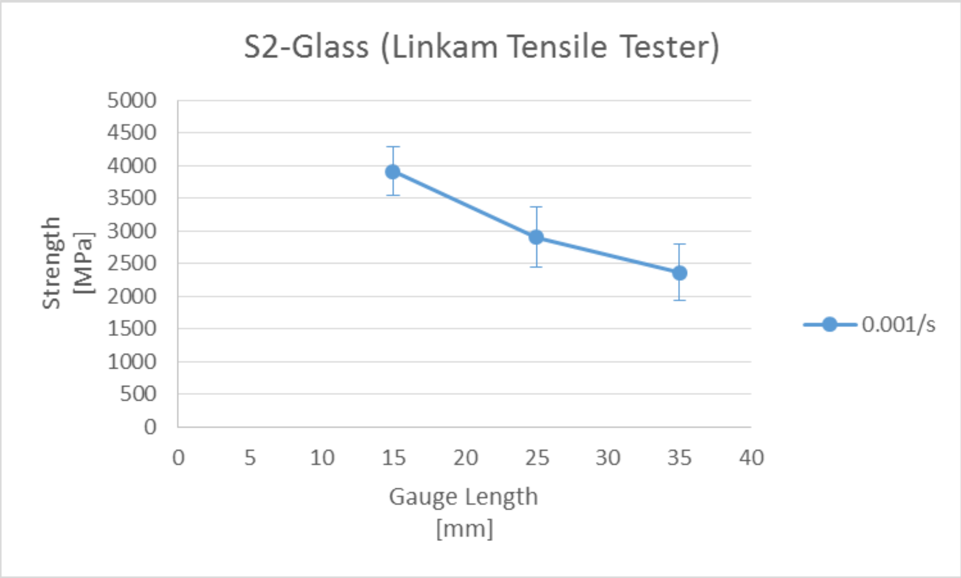

Figure 14 - Tensile strength of S2-Glass® single fibres (Linkam Tensile Tester)

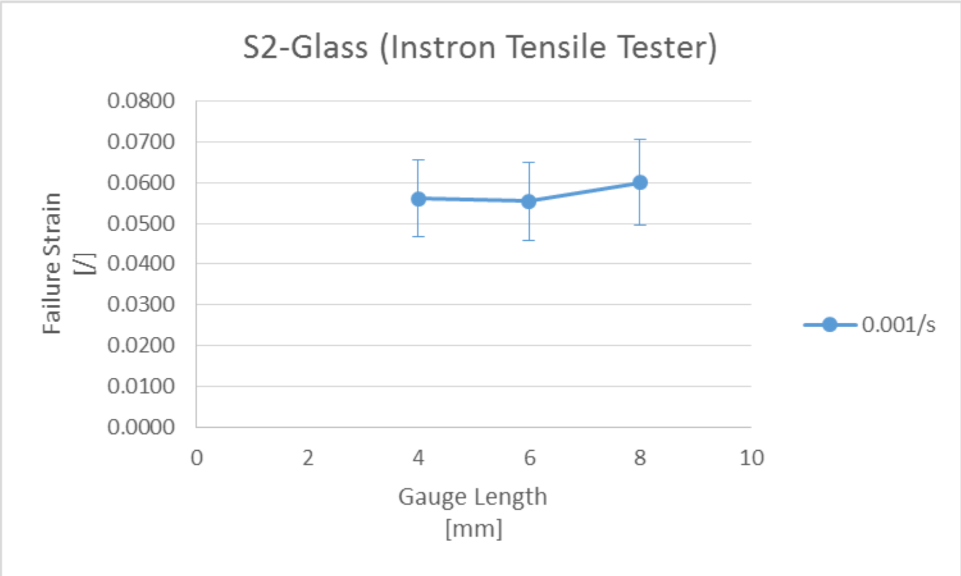

Figure 13 - Corrected Strain at failure of S2-Glass® single fibres (Linkam Tensile Tester)

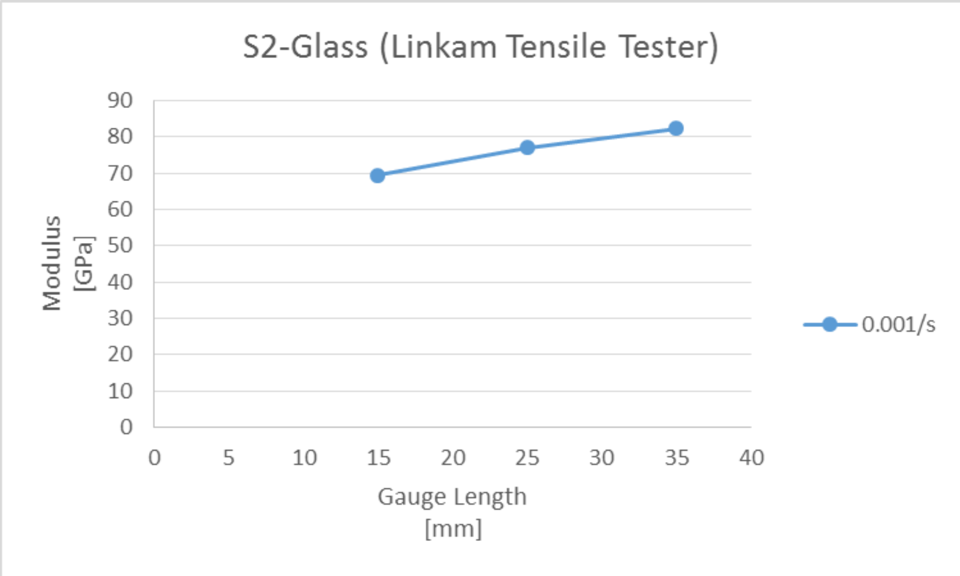

Figure 15 - Corrected Young's Modulus of S2-Glass® single fibres (Linkam Tensile Tester)

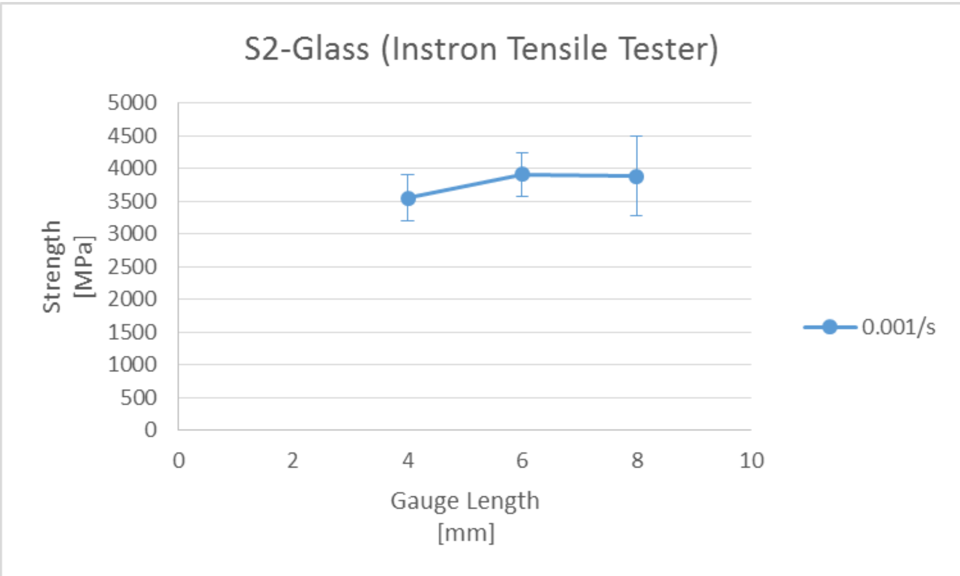

Figure 16 - Tensile strength of S2-Glass® single fibres (Instron Tensile Tester

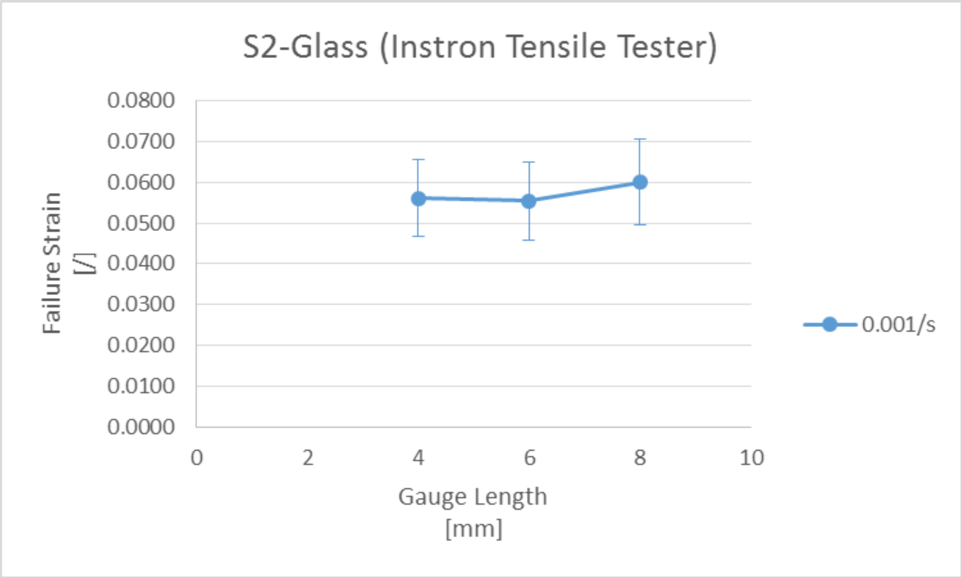

Figure 17 - Corrected Strain at failure of S2-Glass® single fibres (Instron Tensile Tester)

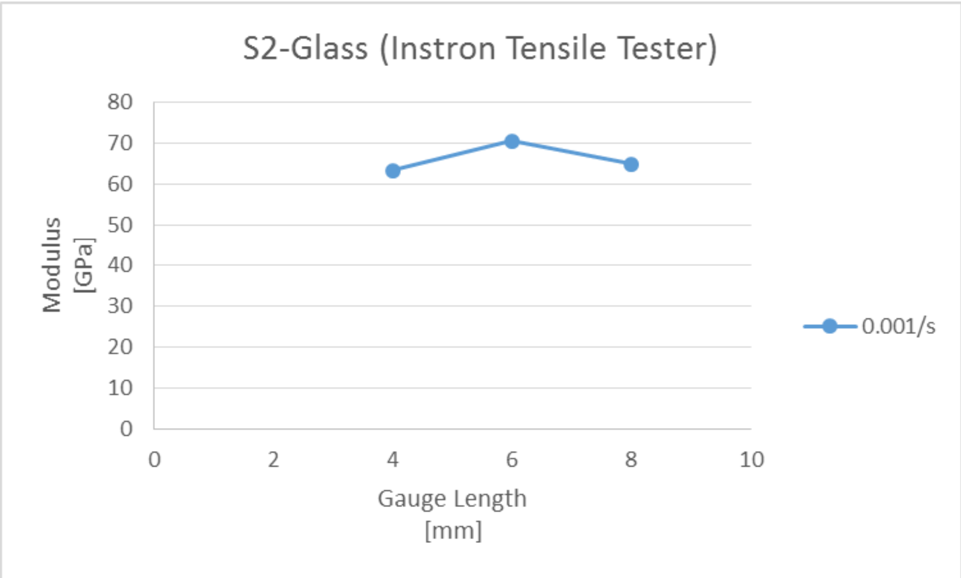

Figure 18 - Corrected Young's Modulus of S2-Glass® single fibres (Instron Tensile Tester)

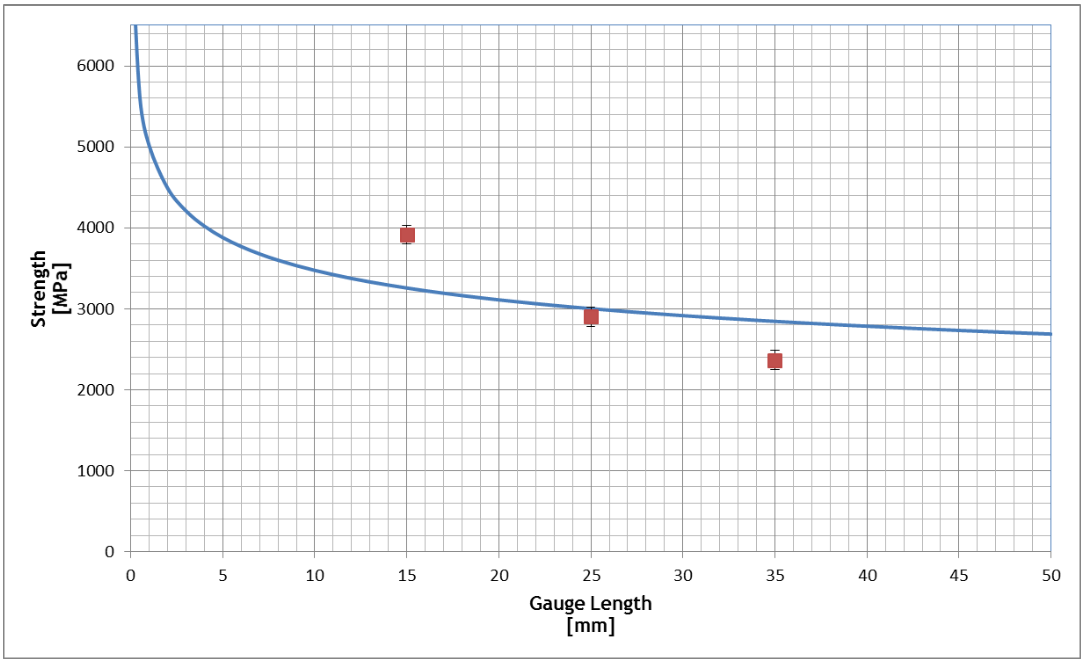

Figure 19 - Weibull analysis for S2-Glass®

Table 6 - Experimental and prediction of S2-Glass® fibres strength

Gauge length [mm]	Strength [MPa]	
	Weibull Analysis	Experimental
4	4021	3550
6	3770	3906
8	3601	3884

S2-Glass® fibres tested using the Linkam Tensile Tester exhibit a significant gauge length dependence. The strength and the strain at failure increased when the gauge length decreased. Although the strength of the fibres tested on the Instron is not the same for the different gauge length it is not correct to say that there is a gauge length dependence. Since the strength practically remains the same, there must be a limit of strength for those fibres and that limit is between 8 and 15 mm gauge length which means that no matter the gauge length under that limit, the strength won't be too far for the results obtained in **Error! Reference source not found.**.

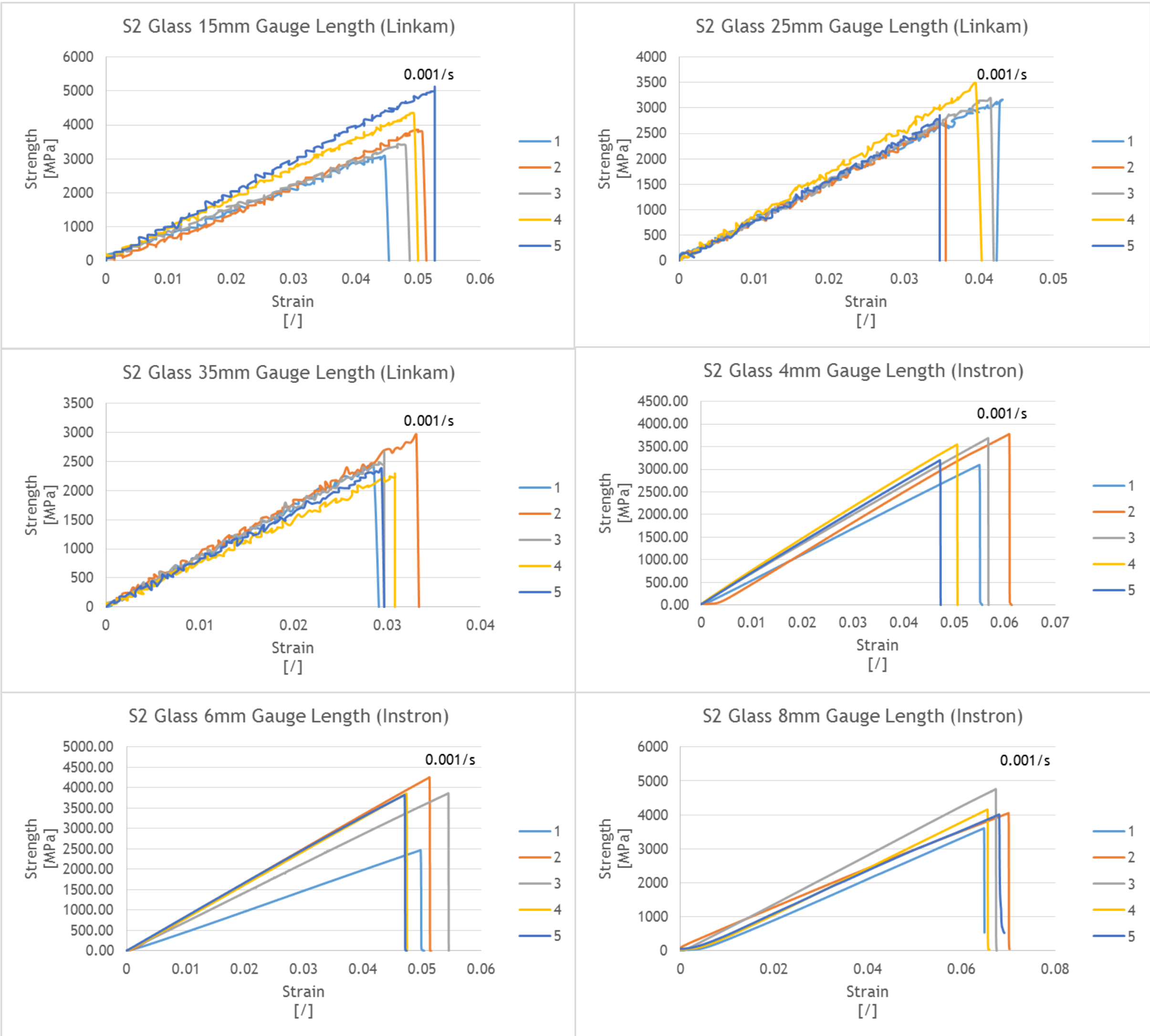

Figure 20 - Typical Stress vs Strain curves (before system compliance correction)

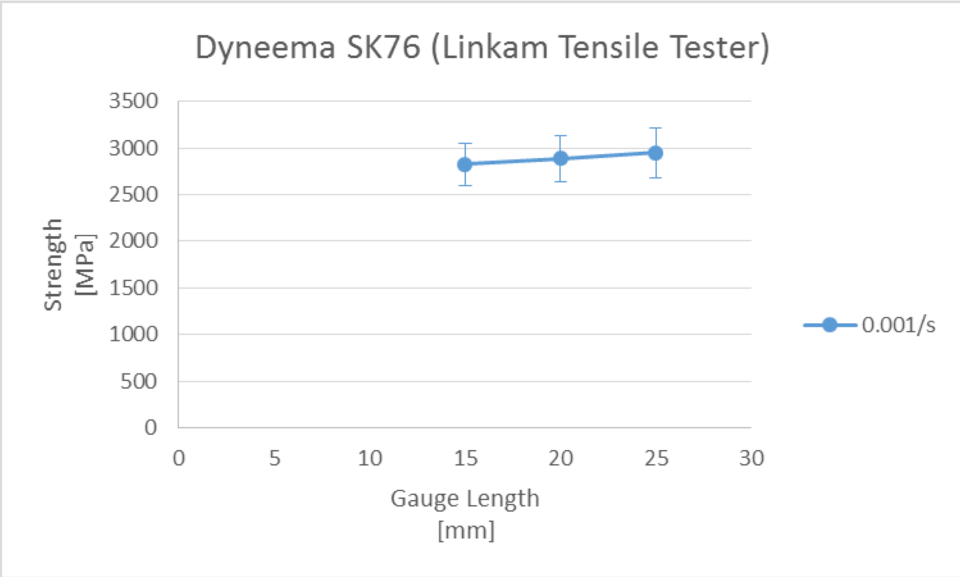

Figure 21 - Tensile strength of Dyneema® SK®76 single fibres (Linkam Tensile Tester)

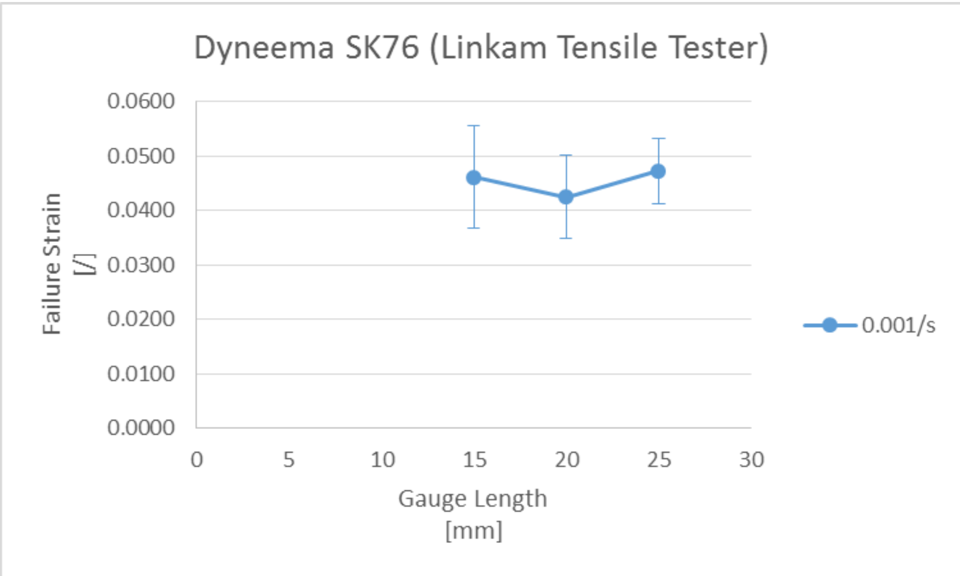

Figure 22 - Corrected Strain at failure of Dyneema® SK76 single fibres (Linkam Tensile Tester)

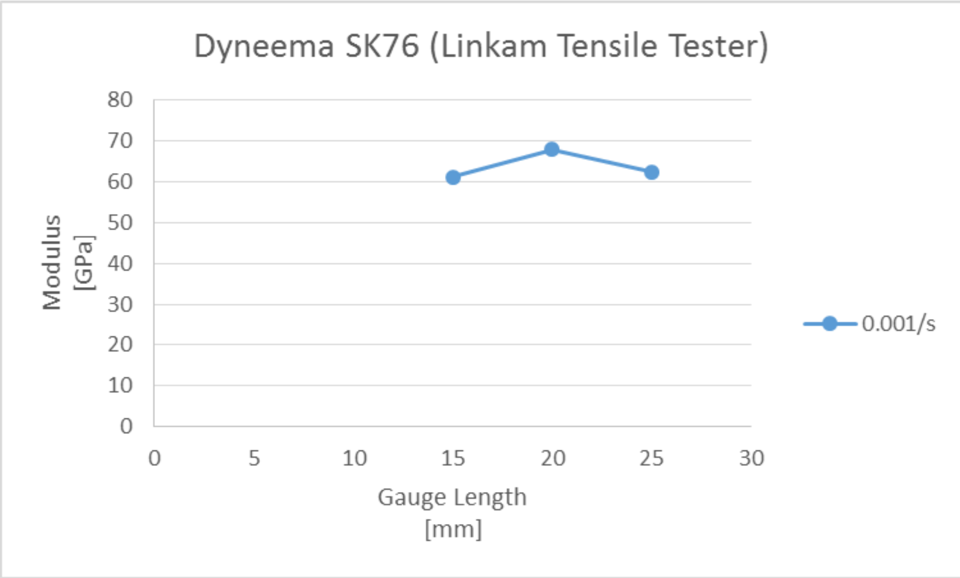

Figure 23 - Corrected Young's Modulus of Dyneema® SK76 single fibres (Linkam Tensile Tester)

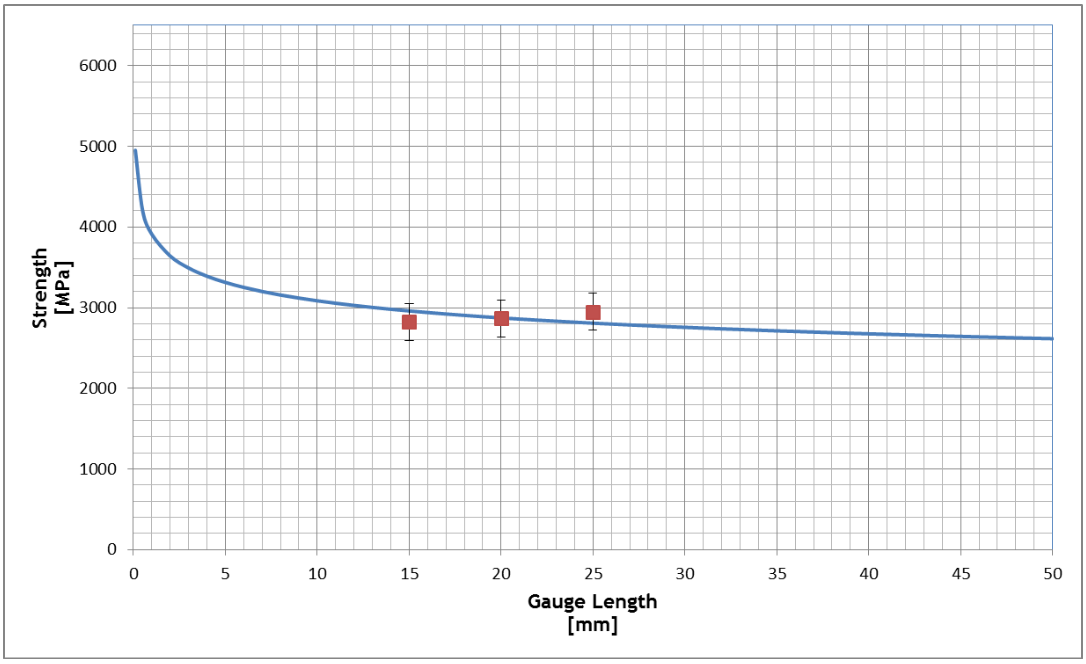

Figure 24 - Weibull analysis for Dyneema® SK76

Dyneema® SK76 fibres were only tested using the Linkam Tensile Tester. However, from the results obtained, the strength is not affected by the gauge length. However, it is not possible to compare the prediction from the Weibull analysis and the experimental results because the fibres were not tested using the Instron 5969 Tensile Tester.

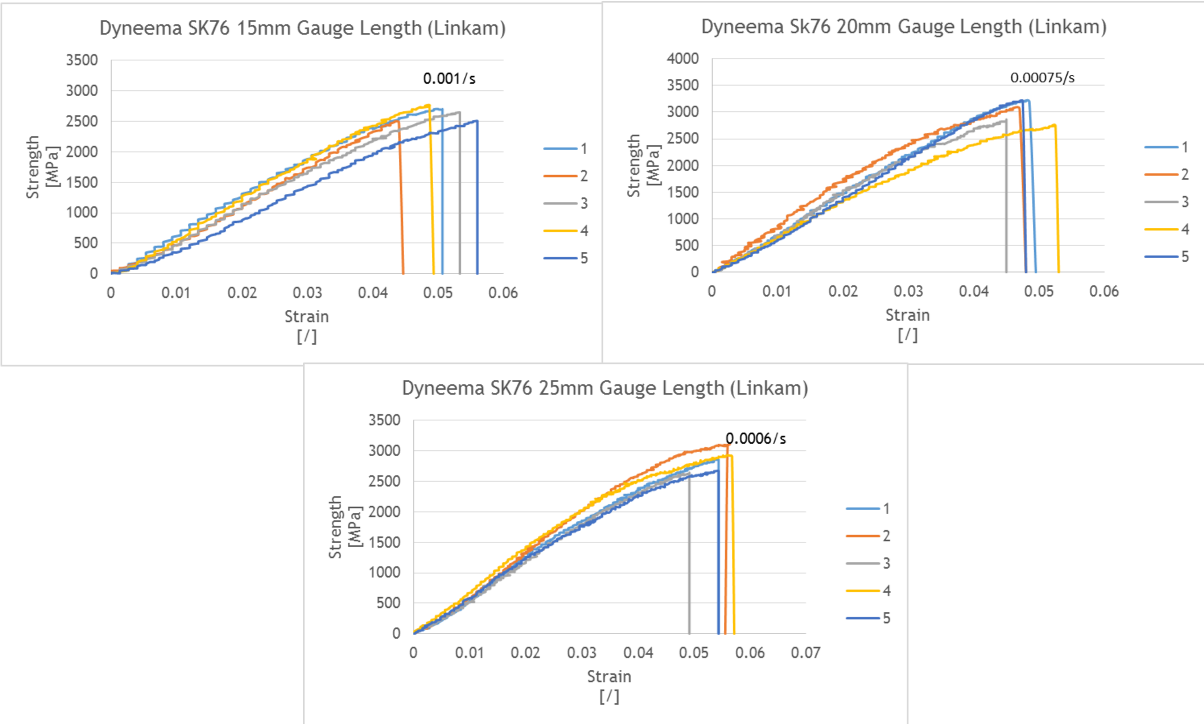

Figure 25 - Typical Stress vs Strain curves (before system compliance correction)

3 Dynamic Tests

3.1 Miniaturized Hopkinson Bar

The miniaturized Hopkinson Bar was developed by Dr. Lucio Raimondo and Prof. Lorenzo Iannucci in which they used the previous split Hopkinson pressure bar and adapted to the new version. This new version, the miniaturized Hopkinson Bar, consists of two titanium bars, with different lengths and diameters, by a striker and a piezoelectric load cell. The input bar consists in a 2.1 m length titanium bar with 12.7 mm of diameter and in a 0.85 m length titanium bar with 4 mm of diameter. The smaller diameter bar is screwed into the other and on the other end there is a silver steel pin where the specimen is glued. The piezoelectric load cell has another silver steel pin where the other end of the specimen will be glued. Both pins are screwed into the titanium and the piezoelectric load cell so that they can be removed after the test and screw two new pins.

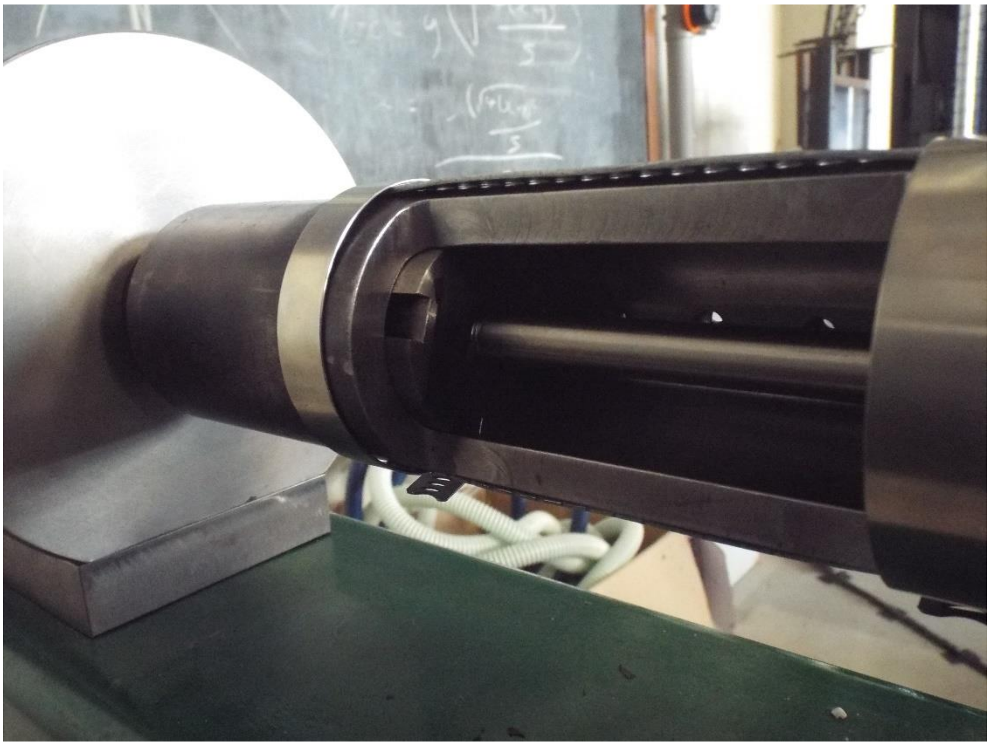

Figure 26 - Flange at the end of the input bar

A striker with 60 cm length is accelerated by an air pressure system and it is fired manually. The pressure at which the striker is fired is controlled so that the test conditions can be repeated. When the striker reaches the end of the 12.7 mm bar there is a flange (Figure 26): the impact between the striker and flange will generate a wave that will run through the 2.1 m length bar and consequently through the 0.85 m length bar (to ensure a constant amplitude wave the flange has black tape). When the wave reaches the specimen, part will be reflected and another part will run through the specimen into the load cell. The wave needs to run through the specimen at least five times before the failure of the specimen breaks, otherwise the test isn't valid (ensure the stress equilibrium).

The piezoelectric load cell, model 113b24, was manufactured by PCB®. Although the sensitivity was known, it was only for compression. So, in order to obtain the strength of the fibres tested, it was needed to do a calibration in tension.

3.2 Piezoelectric load cell calibration

The load cell used to measure the loading on the fibres was only calibrated in compression by the manufacturers. Since the single fibres were tested in tension, it was needed to calibrate the piezoelectric load cell. For the first calibration it was used springs with a known *k* coefficient. The load is the length multiplied by the *k* coefficient of the springs in series, in which the length is the distance between the ends of the springs. Changing the number of springs in series and the length gave different loads and consequently different values read by the sensor. When the springs were stretched, the load applied on the sensor generates an electrostatic charge proportional to the load. This electrostatic charge is amplified and captured by a software (*Picoscope 6*). Figure 27 shows the load and the charge associated.

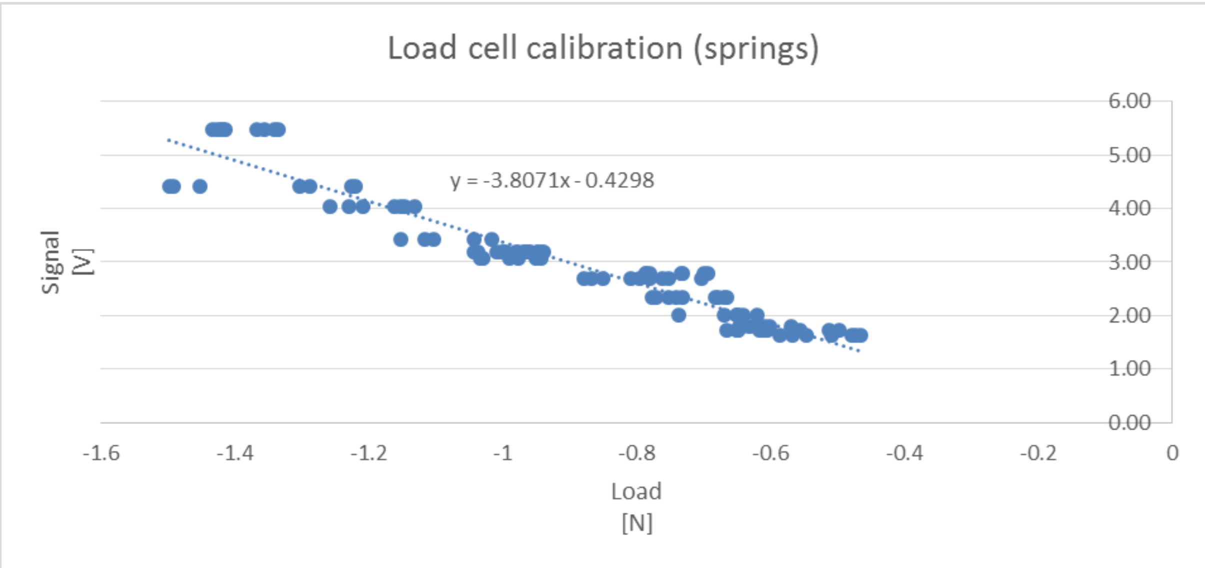

Figure 27 - Calibration of the load cell using springs

To obtain the sensitivity of the load cell, all the results were fitted in a trendline, wherein the slope would give the sensitivity. Unfortunately, the intercept wasn't zero, as it should, so it was made another calibration to confirm the slope obtained by the spring calibration. To do this calibration it was used carbon fibres. Carbon fibres were tested using the miniaturized Hopkinson bar. The results obtained were then compared to the quasi-static results obtained by David [37]. David tested HexTow® AS4C carbon fibres under quasi-static loading conditions. Once again, the results were fitted in a trendline and the slope obtained using the Carbon fibres showed that the first calibration was corrected. **Error! Reference source not found.** shows the slopes obtained by the two calibrations.

Table 7 - Load cell calibration

Test	Sensitivity [N/V]
Springs	-3.8071
Carbon fibres	-3.7357

3.3 Striker Pressure vs Speed curve

Using the high speed camera it was measured the speed at which the striker hits the flange. In order to calculate the relation between the pressure that the striker is fired and the speed that it hits the flange, the striker was fired at different pressures. The results were then fitted in a trendline and the slope was 32778 mm/(s.bar).

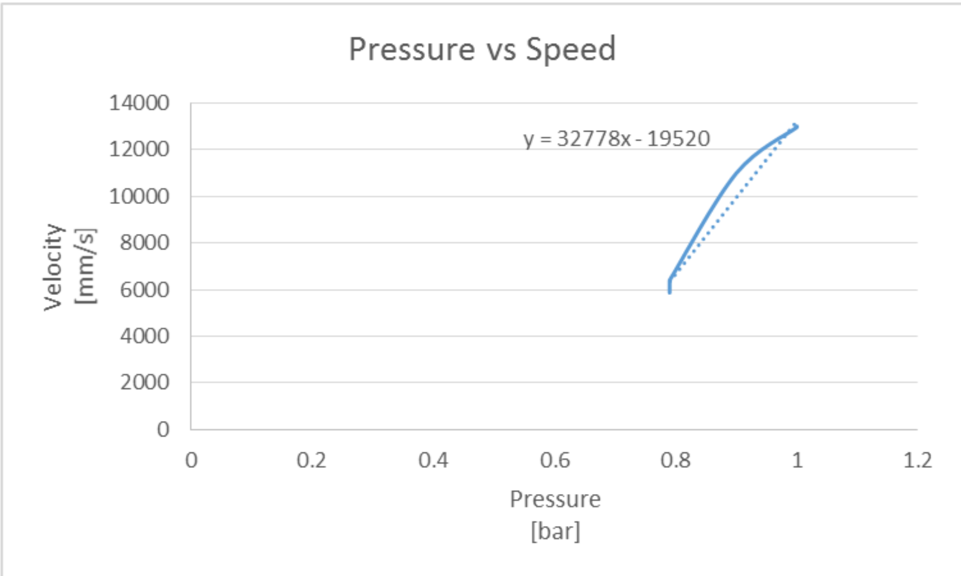

Figure 28 - Pressure vs Speed curve of the Striker

3.4 Fibre preparation

The fibre preparation for the dynamic tests was similar to the quasi-static fibre preparation. The frame template was rectangular with a window larger than the gauge length because this time the gauge length was set by the distance between the ends of the two pins. To avoid that the fibre slip during the test, there is a flat with 7mm length on the pin to increase the bonding length.

3.5 Dynamic Tests

To glue the sample to the pins it was used an epoxy glue, Araldite 2021. This glue need to develop enough shear strength to hold the fibres but in the shortest time possible: as fast this glue develop the shear strength needed, the bigger were the number of tests performed per day. Araldite 2021 took 20 minutes to develop this shear strength (it was reasonable otherwise the test would last too much time).

The distance between the ends of the pins set the gauge length (the distance was measured using a calliper) of the test: the gauge length for Vectran® was 3 mm while for S2-Glass® the gauge length was 2 mm. The method to properly glue these fibre consists in put some glue on top of the pins , then aligned and hold the template using a peg and finally put more glue on top of the fibre. This way the fibre had glue all around and the probability of slippage was diminish. After some tests it was found out that the amount of glue used on this process was very important because if the glue wasn’t enough the fibre would slip.

Twenty minutes after the procedure, the template was cut and the peg removed. To measure the strain it was used a high speed camera that was recording a frame at each 2 microseconds and it was trigger manually, at the same moment that the striker was fired. Given the high frame rate per second, to properly record the video it was needed lights but since the single fibres tested were very sensitive to temperature, the lights used were cold lights. The software used to obtain the loading curve was the *Picoscope 6* that could capture one point of the loading curve at each 2 microseconds. Although the load cell could capture more than 500 000 points per minute, due to a limitation of the software, this was the maximum number of points.

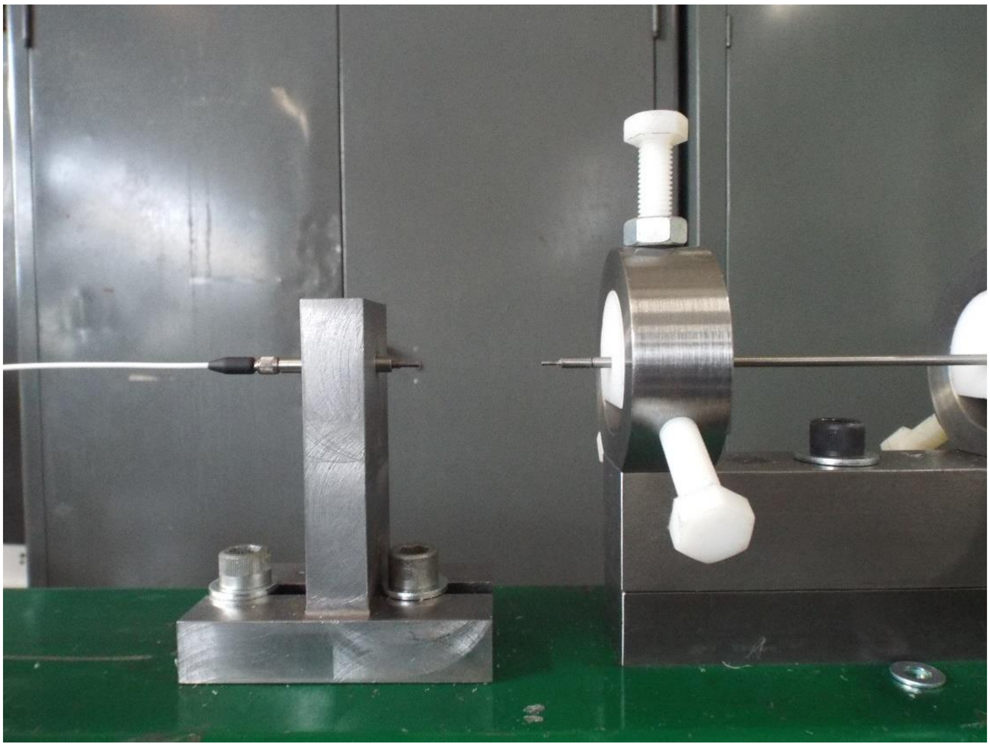

Figure 29 - Piezoelectric load cell and the end of the bar

Figure 30 - Supports and the input bar

3.6 Results and Discussion

The first tests lasted 0.2 seconds, almost one thousand times more than expected. Due to a mismatch impedance between the titanium bar and the specimen, the titanium bars were replaced by aluminium bars with the same length although the diameter of the smaller diameter bar (4mm bar) was increased to 6.35 mm (the diameter was increased to avoid the bending of the bar). Nevertheless, there are eight supports made of a self-lubricated material to align the bars and to support them.

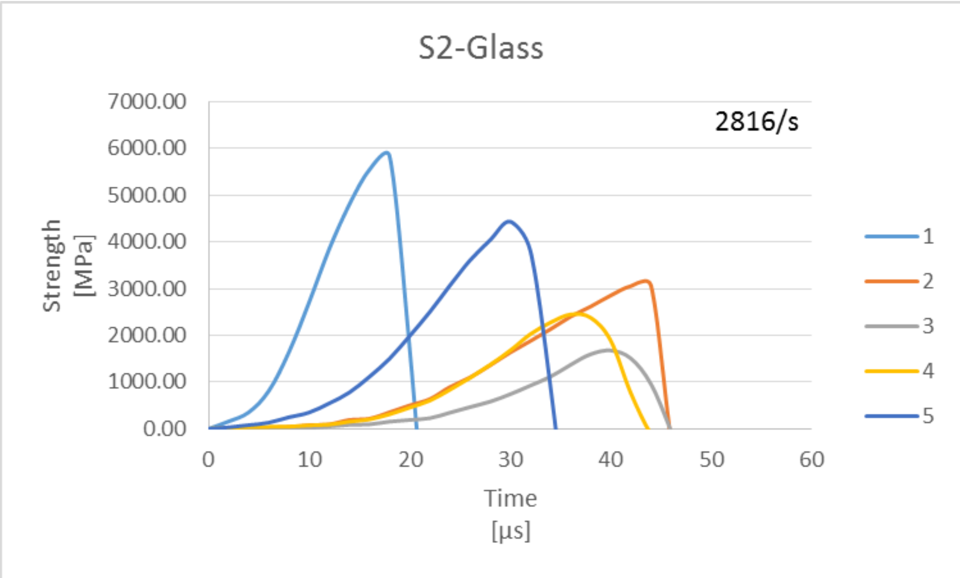

Figure 31 - Typical Stress vs Time curves for S2-Glass® with 2mm gauge length

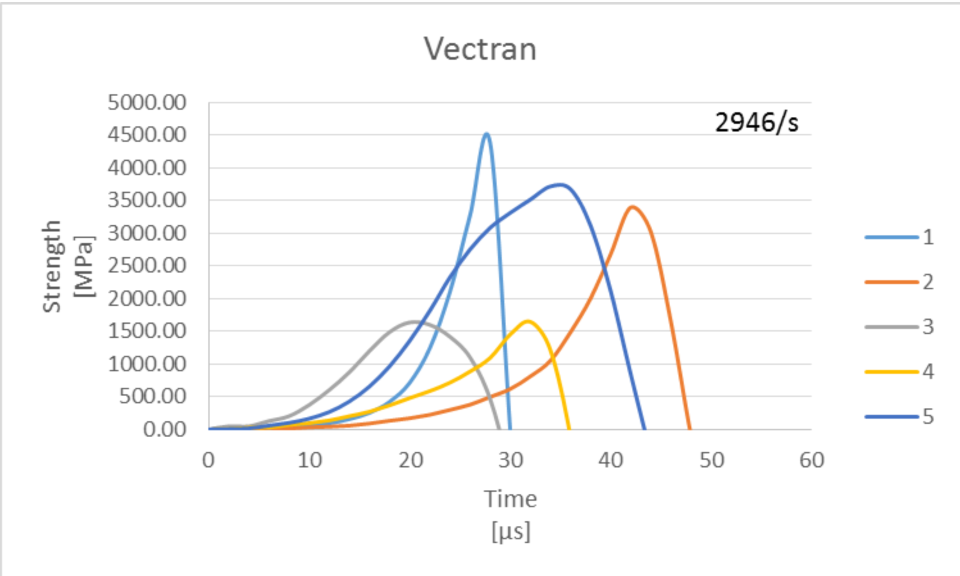

Figure 32 - Typical Stress vs Time curves for Vectran® with 3mm gauge length

Table 8 - Mechanical properties under high strain rates

Material	Radius [m]	Gauge Length [mm]	Strain rate [1/s]	Ultimate Strength [MPa]		Strain [/]	Number of Tests
				Average	Standard Deviation		
Vectran	1.09E-05	3	2946	2934	1080	0.1391	15
S2-Glass	3.73E-06	2	2816	3368	1275	0.0647	15

The striker, for all the tests, was fired at 0.79 bar. Figure 31 and Figure 32 shows the typical stress vs time curves obtained from the tests. **Error! Reference source not found.** shows the mechanical properties obtained under high strain rates.

The strain obtained under high strain rates is before system compliance correction, because it was only tested one gauge length (for system compliance correction it is needed at least 3 gauge lengths). To measure the strain it was used the high speed camera software (*Phantom*) in which the displacement between both ends of the pins was took before the beginning of the tensile test and at the moment the fibre broke. The average ultimate strength obtained under high strain rates is lower than the average obtained under quasi-static which means the ultimate strength is affected by the strain rate. However, the results are highly affected by the handling and alignment of the specimens tested. When observed by a naked eye the fibres look aligned, but when observed by the high speed camera, there is a misalignment on some of the tests. Figure 33 shows the fibre misaligned.

Table 9 - Strength under high and low strain rates

Material	Quasi-static		High strain rate		HSR vs QS
	Gauge length [mm]	Strength [Mpa]	Gauge length [mm]	Strength [Mpa]	[%]
S2-Glass	4	3550	2	3368	-5
Vectran	4	3937	3	2934	-25

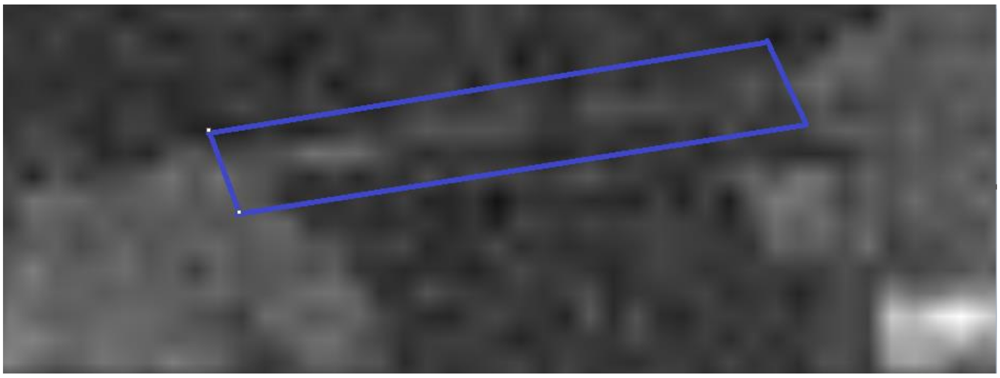

Figure 33 - FIbre misaligned

4 Conclusions and Future work

4.1 Conclusions

In this thesis, it was performed single fibres tests under high strain rates and under low strain rates. In order to investigate the dynamic behaviour of high performance fibres, it was performed single fibres tests at quasi-static conditions using an Instron 5969 and a Linkam TST350 to compare both behaviours.

From the quasi-static tests it was possible to realize that the Weibull analysis cannot be used to predict the strength of Vectran® fibres. The strength of Vectran® is not affected by the gauge length and it seems there is a limit of strength for these fibres which is under 4GPa. S2-Glass® fibres exhibit a gauge length dependence, although this dependence is more significant between 15 and 35mm. Under 15mm, the strength does not change, which may indicate that the limit of strength of these fibres has been reached. Dyneema® SK76 fibres weren't tested under high strain rates because the fibres slipped through the glue while being tested using the Linkam TST350 Tensile Tester.

The dynamic strength of Vectran® and S2-Glass® is lower than the quasi-static strength: S2-Glass® strength diminished 5% while Vectran® strength diminished 25%. Although it was tried to align the fibres, and at naked eye they look aligned, using the high speed camera it was possible to realize that some of the fibres tested weren't in fact aligned. This misalignment affected the strength.

4.1 Future Work

As previously discussed, during the project it was found some problems that with more time would certainly be resolved. One of them was that sometimes after fire the striker, due to its small diameter, the striker was touching the 12.7 mm bar and then the bar moves before the striker hits the flange. This affect the results because the fibre was being stretched before the wave runs through it increasing the time that the test lasts and decreasing the strain rate.

Another problem faced was the glue used to glue Dyneema® fibres. If it was possible to test Dyneema® SK76 fibres under quasi-static strain rate using a low viscosity cyanoacrylate, under high strain rate the fibre slipped using the same glue.

Although the results obtained using the miniaturized Hopkinson bar are reasonable, due to the glue used, the time to test one fibre was too long (glue the fibres plus test it dynamically). Araldite 2021 was more than enough to hold the fibres during the test but for a test as fast as 100 microseconds (the worst scenario), 20 minutes is too much. To solve this problem it could be used a different glue, although this was the best found, or develop a clamping system.

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