

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Strengthening for improved fatigue capacity of railway bridges

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Master's Degree in Mechanical Engineering

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Resumo

As pontes ferroviárias metálicas assumem uma parte fundamental para a rede de caminhos-de-ferro, uma vez que permitem que os comboios cruzem rios, vales, entre outras barreiras naturais ou artificiais, sendo também essenciais para o transporte de cargas e pessoas. Por estes motivos, as pontes ferroviárias encontram-se permanentemente sujeitas a cenários de tráfego, provocados por carregamentos complexos, responsáveis pelo desenvolvimento de respostas locais que, dependendo da sua severidade poderão originar danos por fadiga. Por serem utilizadas recorrentemente, as pontes ferroviárias exigem uma constante manutenção, deste modo e devido a muitas já possuírem em geral uma idade considerável, torna-se necessário ter em conta este fator, para se prever danos estruturais consequentes do volume de tráfego ferroviário pesado. Através desta previsão é possível perceber como proteger e reabilitar estas infraestruturas.

O fenómeno de fadiga com o passar dos anos tornou-se cada vez mais uma preocupação, devido a ser uma ameaça à integridade estrutural, sendo necessário conseguir obter alternativas para solucionar ou atrasar o seu desenvolvimento.

Tendo em conta este contexto, tem-se vindo a desenvolver metodologias multiescala para a aplicação de métodos locais de fadiga, de forma a reduzir o conservadorismo excessivo que pode estar associado à aplicação de métodos globais de fadiga, sugeridas pelos Eurocódigos aplicáveis. Além da análise estrutural para avaliar a resistência à fadiga, importa desenvolver métodos de reforço global e local de forma a aumentar a vida útil das pontes para maiores volumes de tráfego. Entre estas, o uso de CFRPs (Carbon Fiber Reinforcement Polymers) para melhorar a resistência de detalhes críticos à fadiga tem vindo a ser considerada, sendo fulcral a proposta de métodos para dimensionar este reforço.

O presente trabalho visa desenvolver um modelo para a avaliação da resistência à fadiga quando se aplica uma banda de CFRP nas proximidades da zona mais sensível a este fenómeno. Para iniciar o estudo foi realizada uma análise num exemplo mais simples, para verificar a exequibilidade do modelo. Feita a confirmação foi depois possível passar para o caso de estudo real da Ponte de Várzea, onde se avaliou a influência da banda de CFRP quando colocada nas proximidades da zona rebitada.

A realização dos casos de estudo mais simples revelaram uma constatação significativa: a aplicação de CFRP numa das faces do elemento estrutural pode ter efeitos contraproducentes se resultar numa flexão local fora do plano da placa. Além disso, foram obtidas informações cruciais relativamente às dimensões e localização da banda, tendo em conta o tamanho do furo e a espessura da placa, proporcionando assim, a possibilidade de um uso mais eficaz do CFRP.

Esta abordagem foi realizada recorrendo ao software *ANSYS*, com o objetivo de retirar as tensões e conclusões necessárias no decorrer do trabalho.

Abstract

Metallic railway bridges are a fundamental part of the railway network, as they allow trains to cross rivers, valleys, among other natural or artificial barriers, and are also essential for the transport of cargo and people. For these reasons, railway bridges are permanently subject to traffic scenarios, caused by complex loads, responsible for the development of local responses that, depending on their severity, may lead to fatigue damage. Because they are used recurrently, railway bridges require constant maintenance. Therefore, and due to the fact that many of them are already of considerable age, it is necessary to take this factor into account in order to predict structural damage resulting from the volume of heavy railway traffic, as already mentioned. Through this prediction it is possible to understand how to protect and rehabilitate these infrastructures.

The phenomenon of fatigue over the years has become increasingly a concern, as it is a threat to structural integrity, and it is necessary to obtain alternatives to solve or delay its development.

In view of this context, multi-scale methodologies for the application of local fatigue methods have been developed in order to reduce the excessive conservatism that may be associated with the application of global fatigue methods, suggested by the applicable Eurocodes. In addition to structural analysis to assess fatigue resistance, it is important to develop global and local strengthening methods in order to increase the service life of bridges for higher traffic volumes. Among these, the use of CFRPs (Carbon Fiber Reinforcement Polymers) to improve the fatigue resistance of critical details has been considered, and the proposal of methods to size the reinforcement to be applied is crucial.

The objective of this study is to develop a model for evaluating fatigue resistance when applying a CFRP patch near the zone most susceptible to this phenomenon. To commence the investigation, it is conducted an analysis using a simpler example to confirm the feasibility of the model. With this confirmation, it is possible to proceed to the real-world case study of the Várzea Bridge, where we assessed the impact of the CFRP patch when positioned in close proximity to the riveted area.

The simpler case studies yielded a significant revelation: the application of CFRP on one side of the structural element can yield counterproductive results if it induces local bending outside the plane of the plate. Furthermore, it is acquired important insights into the dimensions and positioning of the patch, considering the hole size and plate thickness, thereby offering the potential for a more effective utilization of CFRP.

This approach was carried out using *ANSYS* software in order to draw the necessary stresses and conclusions as each example was analysed.

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*“O conhecimento é o que temos de mais especial,
porque isso nunca ninguém nos tira.”*

Avó Trindadinha

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Abbreviations and Symbols

A	Alternating ratio
a	Length of the crack and crack size
a_c	Critical length
$BDCO_S$	Boundary conditions
$BDCO_{S_j}$	Boundary conditions of the j the vibration mode
$BDCO_{S_{SW}}$	Part of the $BDCO_S$ due to the permanent loading
C	Dimensionless constant
CFRP	Carbon-fiber-reinforced polymers
da/dN	Crack propagation rate
E	Young modulus
EU	European Union
f_u	Fatigue strength
G	Energy release rate
G_I	Energy release rate for mode I
G_{II}	Energy release rate for mode II
G_{III}	Energy release rate for mode III
G_{Ic}	Critical energy release rate
K	Strength coefficient
K_c	Material toughness or critical stress intensity factor
K_t	Stress intensity factor
K'	Cyclic strain hardening coefficient
K_I	Stress intensity factor for mode I
K_{II}	Stress intensity factor for mode II
K_{III}	Stress intensity factor for mode III
K_{Ic}	Critical stress intensity factor
N	Loading cycle
n	Strain hardening coefficient
n'	Cyclic strain hardening exponent
R	Stress ratio
REFER	National Rail Network
TENT-T	Trans-European Transport Network
Y	Dimensionless shape factor
Y_j	modal coordinates of the j^{th} vibration mode
ΔK	Range of stress intensity factors
$\Delta\sigma$	Local stress range
ε	Notch strain
ε_p	Plastic strain
μ_{FDF}	Fatigue damage factor
ν	Poisson's ratio

σ	True stress
σ_a	Alternating stress
σ_m	Mean stress
σ_{max}	Maximum stress
σ_{min}	Minimum stress
σ_{nom}	Nominal stress range
σ_o	Nominal stress
σ_{f0}	Fatigue limit for $\sigma_m=0$
ϕ'	Amplification factor for dynamic loading
ϕ''	Amplification factor for irregularities of the track

Chapter 1

Introduction

1.1 Context

Since the 1830s, the railway network has demonstrated a consistent growth, leading to the development of a dense stock of railway bridges. These railway structures are constantly changing structures, reliant on maintenance, repair, and replacement to ensure both their functionality and preservation value. The advent of rail transport in Europe during the 19th century sparked a rapid global expansion, revolutionizing transportation with its increasing speed, safety, convenience, and cost-effectiveness. To enhance rail circulation, bridges were first constructed using materials such as wood and cast iron. However, over time, it became evident that these materials were unsuitable for bridge construction, prompting their replacement by wrought iron, and subsequently, steel or concrete. The escalating demand for this mode of transportation required expedited bridge construction, catalyzing advancements in construction methodologies. In 1875, the introduction of steam cranes revolutionized these endeavors, accelerating execution speed significantly, figure 1.1. This method not only facilitated the handling of materials but also enabled the construction of bridges with larger elements as they continued to evolve [1].



Figure 1.1: Steam Navy used in construction of the great central railway [1]

The remarkable evolution of the railway concept has spurred a soaring demand for increasing speeds, owing to their crucial role in enhancing the overall efficiency and growth of the transport system. While the railway system showcased numerous advantages during its inception, it faced a

decline in competitiveness during the first half of the 20th century compared to air and road transport. Nevertheless, the appearance of high-speed trains, sparked a revival of rail as a formidable and competitive mode of transportation for specific routes. In present day, sustainable development strands as one of the paramount global challenges, rendering transportation development all the more significant. In this regard, railway emerge as a central pillar for driving transformative climate action in the transport sector, boasting various economic, environmental, and social advantages [2]:

- **Efficient Transportation:** Railways are well-known for their high-speed transportation capabilities, making them an effective form of transportation for both goods and people. Trains may cross over barriers like rivers and valleys using railroad bridges without slowing down or stopping the movement of the rail network;
- **Environmentally Friendly:** Railways are an environmentally benign source of transportation since they produce less greenhouse gases than other modes of transportation. Furthermore, compared to other types of infrastructure, railway bridges don't necessitate much in the way of land clearing or environmental modifications;
- **Reduced Traffic Congestion:** Railways, railway bridges, and other modes of transportation can all contribute to lessen traffic on roads and highways. There are fewer vehicles on the road and less traffic since trains can transport a lot of cargo and passengers at once;
- **Cost-Effective:** Compared to other modes of transportation like the air or road, railways can convey a lot of cargo and people for a lot less money. In addition, railway bridges require less upkeep than other forms of infrastructure, which can save money over time;
- **Safety:** Railway infrastructures are designed and built to high safety standards, making them a safe mode of transportation. Railway bridges are designed to withstand high loads, extreme weather conditions, and other environmental factors, which helps ensure the safety of passengers and cargo.

In addition to climate change, the rail industry plays an important social role concerning the preservation of the ecosystem and biodiversity in both rural and urban areas [3]. Moreover, there is a vision to integrate the railway infrastructure seamlessly into the natural landscape, forging connections between different biotopes and facilitating species migration. This ecological approach aims to create diverse habitats for numerous species, effectively transforming the railway network into a flourishing "green network" [3].

In pursuit of climate neutrality by 2050, the European Commission unveiled the "European Green Deal" in 2019, which outlines a crucial objective. According to that initiative, a significant portion of the current 75% of goods transported by land on highways must be transferred to rail corridors and navigable interior waterways [2]. Also, for the EU to remain economically competitive and to pursue a balanced and sustainable development, it is crucial to build the trans-European transport network (TENT-T), which is based on the connectivity and interoperability of national transport networks, including rail [4].

In the Portuguese context, one of the most momentous events during this period was the inauguration of the railways on the 28th October 1856. This landmark occasion marked the beginning

of numerous significant milestones in the history of transportation. From the initial plan to construct a rail connection between the country's second city, Porto, and the border at Badajoz, the railway network has since expand to include both domestic and international destinations. This extensive growth has played a vital role in propelling the nation's development and forging closer ties with the rest of Europe [5].

Notwithstanding recent technological breakthroughs and almost a century of urban and industrial expansion, the Portuguese railway map is essentially unchanged from that of the early 20th century [6]. This event was due to an intense process of dismantling railway lines, between 1980 and 2015 which took place not only on Portuguese territory. Table 1.1 enables an analysis of railway dismantling activities since 1969, displaying both the year of dismantling and the length of decommissioned track.

Table 1.1: Dismantled railway lines since 1969 [6]

Railway lines	Dismantlement year	Length (Km)
Linha de Guimarães	1989	56
Linha do Minho	1990	16
Linha Porto - Póvoa - Famalicão	2002	57
Linha Douro	1998	28
Ramal de Alfândega	1989	4
Linha do Tua	1992	130
Linha do Corgo	2011	96
Linha do Tâmega	2011	55
Linha do Vouga	1990	79
Linha da Lousã	2010	30
Linha do Dão	1989	49
Linha de Leste	2011	141
Ramal de Cáceres	2011	72
Vendas Novas-Setil	2011	70
Ramal de Montemor	1987	13
Ramal do Montijo	1987	12
Linha do Sueste	1990	42
Linha de Portalegre	1990	20
Ramal de Seixal	1969	4
Ramal de Sines	1990	48
Linha de Évora	2011	102
Linha do Guadiana	1990	41
Linha de Guimarães	1989	56
Linha de Mora	1987	60
Ramal de Aljustrel	1976	11
Total of deactivated lines		1236

The introduction of the railroad in Portugal, provided several changes, including the relationship between urban centres and rural areas, since previously the transportation occurred mostly by waterways. Thus, after the inauguration of the first railway line in 1856, large cities such as Porto

and Lisbon showed a greater ease in transporting goods and people by land, not only nationally, but also internationally.

The emergence and expansion of the railway in Portugal were notably driven by external pressures, as its primary aim was to enhance economic and financial aspects.

The introduction of the railway in Portugal sought to significantly improve transportation in a more cost-effective manner, especially across vast stretches of the country where regional land connections were limited. However, with the passage of time, a shift occurred, favoring freight transport over passenger travel, thereby leading to a reduced impact on the urban scale.

Nowadays, the railway transport has a secondary position in the national transport system, due to the reduced impact of these infrastructures in the country.

Currently, this form of transport increasingly supports tourism and port activities, a trend supported by European Union (EU) railway policies in order to standardize European railroads, connecting several countries [6].

Railway structures are constantly subjected to complex dynamic loads, which consequently lead to structural problems to be considered in their design. Among all the possible structural problems, it is important to highlight the most worrying one, that is, fatigue phenom, since it can be responsible for the development and propagation of serious cracks. Fatigue is a phenomenon that consists in the decrease of resistance of a body when it is subjected to systematic and cyclic loads [7]. This process has as a consequence of local structural degradation, which a riveted railway bridge accumulates over time, and may cause local or global collapse.

In the case under study, riveted railway bridge, it is verified that fatigue is a problem for maintaining the safety of railway bridges, since they are constantly subjected to multiple variable cyclic loads, which, when not investigated and predicted, can present catastrophic effects. It is also important to highlight that the fatigue phenomenon has only started to be considered in mid last century constructions, and therefore there are several structures in need of maintenance due to the growth of traffic that can lead to degradation of structural integrity. To evaluate fatigue damage, different procedures can be used, among them the global and local stress method, notch strain method, methods based on Fracture Mechanics. Global S-N methods, included Eurocode 3, are the most considered ones, which relate the range of applied nominal stress and fatigue resistance [8].

Nevertheless, those global methods have some limitations, since they cover a small number of structural details and do not take into account the influence of material properties, with S-N curves being generally applicable to a wide range of materials, and the possibility of existing cracks is not considered since no distinction is made between crack initiation and crack propagation. That said, a preference for local stress-life methods, notch strain methods and fracture mechanics based methods, alone or in combination, is increasingly apparent as they are more accurate [2].

Fatigue failure can result in considerable casualties and economic losses. In order to counteract this failure, many studies have focused on the feasibility and efficiency of different strengthening methods, among them the application of carbon fiber reinforced polymer, CFRP's, which proved to be effective and practical for the mentioned situation [9, 10, 11].

Taking into account the present context, the main goal of this work is to study the influence of CFRP strengthening strategies in metallic construction, providing to the reader a complete understanding of the impact on local stress and strain fields. Also, a real case study is going to be investigated and relevant conclusions are derived, which contribute to the evolution of the state of the art.

1.2 Objectives

In spite of notable research in simplistic applications of CFRP paths to strength metallic components, as exemplified by the studies conducted by Mohabeddine et al. [10] and Tawfik et al. [11], the translation of these findings into practical real-world situations has remained largely uncharted. This void in exploring practical implementation underscores the heightened importance of the current study.

To achieve the overall goal, several intermediate objectives have been delineated, including:

- Investigating the relevance of fatigue in steel bridges while being mindful of the aforementioned structural concern;
- Conducting a systematic examination of simple case studies to verify expected outcomes;
- Progressing to real-world applications and thoroughly analyzing their implications;
- Explore into potential future applications;
- Providing modeling recommendations.

The assessment of the impact of strengthening techniques is accomplished through their application to simpler case studies. The significance of integrating these approaches in a multiphase methodology for predicting the fatigue life of existing metallic railway bridges, becomes apparent when complex and real case studies are investigated. This exploration aims to elucidate the applicability limits of these methods to contemporary structures.

1.3 Dissertation Structure

The present study is thoughtfully structured into six chapters, each designed to effectively address the proposed objectives.

Chapter 1 serves as the dissertation's opening, with an introductory section. This section offers valuable insights into the background and motivations behind the research. Furthermore, it precisely outlines the primary objectives and noteworthy contributions of the study. A clear and comprehensive overview of the thesis structure and organization is also presented.

Chapter 2 delves into a comprehensive literature review, exploring the current state of the art in assessing the fatigue concepts and its implications for critical components in existing bridges. In addition to examining fatigue-related aspects, this chapter also investigates the performance of CFRPs when utilized as reinforcement for metallic details subjected to dynamic stresses.

Chapter 3 focuses on the numerical assessment of the impact of CFRP application adjacent to an idealized simple notched plate. It also aims to evaluate the behavior of the stress concentration factor (K_t) by analyzing the variations of specific parameters within the examined case study.

In chapter 4, the study unveils the analysis of a real-life case study, namely Várzeas Bridge. Building upon the results and findings obtained in chapter 3, this segment aims to conduct a numerical investigation of the application of CFRPs to a critical detail susceptible to fatigue in Várzeas Bridge. The objective is to assess the impact of CFRP implementation on the modification of the stress concentration factor (K_t).

To conclude the dissertation, two essential chapters remain, namely chapter 5 and 6. Chapter 5 encapsulates the most significant findings and conclusions derived from the comprehensive study conducted throughout the thesis. This chapter serves to provide a concise and insightful summary of the research's key outcomes. Moving forward, chapter 6 serves as a platform to propose other relevant developments that could enhance the capabilities of the proposed methodology, and potentially introduce innovative approaches. It also aims to offer valuable insights into potential areas of exploration and expansion for further research and advancement.

Chapter 2

Fatigue Phenomenon

In this chapter, an introduction to the state of the art concerning the subject fatigue phenomenon is provided, with the purpose of gaining a better understanding of the study to be undertaken.

2.1 Introduction

Humanity has long endeavored to surmount physical constraints put on them, in order to achieve better and more pleasant living situations. This difficulty has been overcome due to the extraordinary efforts in the creation. During the industrial revolution, the emergence of steel as a structural material, alongside the mass production of iron, ushered in groundbreaking advancements in structural systems and building techniques.

A substantial portion of the infrastructure stock in many nations comprises diverse types of steel railway bridges. Nevertheless, as these structures age and traffic loads increase, the deterioration of bridges is becoming a concerning issue, primarily due to structural fatigue [12]. When a material or component is subjected to repeated dynamic loads, a phenomenon known as fatigue occurs. This progressive deterioration may eventually lead to failure, a process that often remains unnoticed until it reaches a critical point, triggered by a single, rapid application of stress.

A wide variety of mechanical systems, including automobiles, bridges, and pipelines, are susceptible to this phenomenon. The severity of fatigue depends on factors like the level of stress and frequency of loading, material properties, and environmental conditions.

Metallic Bridges, renowned for the strength, durability, and flexibility, are particularly prone to experiencing high levels of fatigue damage. This susceptibility is mainly dependent on the traffic scenario, which over time can result in structural harm or even failure. The repeated cycles of loading and unloading give rise to the formation and growth of tiny cracks, ultimately leading to the degradation of the bridge's integrity [13].

This chapter comprehensively covers the main aspects related to the fatigue process, encompassing an examination of failures in old bridges, potential analysis methods, and proposed solutions to enhance to increase the service life of railway bridges. Additionally, various types of

strengthening selection are discussed, with a particular emphasis on CFRP patch reinforcements.

2.2 General aspects of fatigue

The term "fatigue of materials and structural components" strictly refers to deterioration and fracture induced on by cyclic applied loads. In the most serious cases, when this phenomenon results in the formation of a crack, the structure becomes unstable and, in some situations, even unusable.

Environmental factors have an crucial impact on both the mode of damage and the resulting fracture. For instance, at higher temperatures, most materials exhibit plastic behavior, while metals demonstrated creep, and polymers display thermo-plastic behaviour. At lower temperatures, metals lose some of their ductility, increasing the likelihood of brittle fracture. In certain situations and applications, a combination of cyclic loads and fluctuating thermal activities may lead to mixed phenomena such as creep fatigue, creep acceleration by vibration, and thermo-fatigue.

In addition to cyclic loading, the delayed fracture can also occur under steady or gradually changing loading conditions. For example, delayed fracture of polymers and the initiation and propagation of cracks in metals can take place when active environment and non-cyclic stresses are combined. Another common occurrence is corrosion fatigue, which arises from the coexistence of fatigue and corrosion. Conversely, stress corrosion cracking represents the opposite type of damage. These various phenomena may combine to give rise to a type of damage known as static fatigue.

The process of damage build-up known as fatigue operates on a variety of scales, starting from the level of the dislocations, crystal, and other microstructured entities and progress to the level of structural elements. This progression can be observed and verified through various means, figure 2.1.

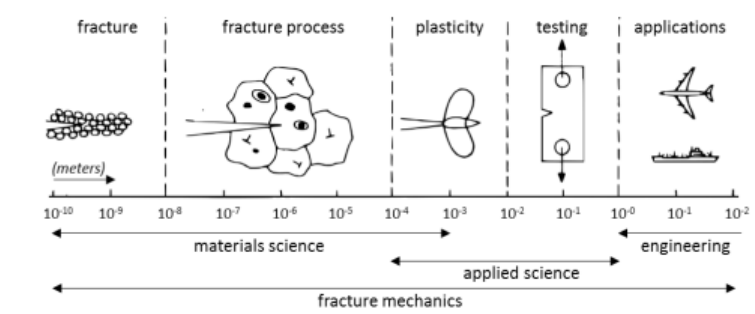


Figure 2.1: The extensive range of applications for fracture mechanics [14]

The process of fatigue damage can typically be distinguished in three or four stages, figure 2.2. During the first stage of the damage, when dealing with a polycrystalline alloy, damage accumulates at the level of grains intragranular layers. This damage tends to cover a significant portion of the specimen's volume or, at the very least, the areas under the highest stress, eventually leading to the formation of a macroscopic crack.

Moving on to the second stage, we observe the growth of shallow cracks in comparison to the size of the cross-section. The dimensions of these cracks are also comparable to a number of distinctive microstructure scales, such as a number of grain sizes. Referred to as small cracks, they propagate differently from fully grown macroscopic cracks. The nonhomogeneous material develops small cracks, with most of them coming to a halt when encountering a barrier. However, one or more may progress into macroscale, long fatigue cracks, which act as strong stress concentrators, marking the damage progress to the third stage of fatigue.

The fourth and final stage is characterized by a rapid final fracture, resulting from a strong stress concentration at the crack front and/or from the depletion of the material's fracture resistance [15], reaching the material toughness, K_c .

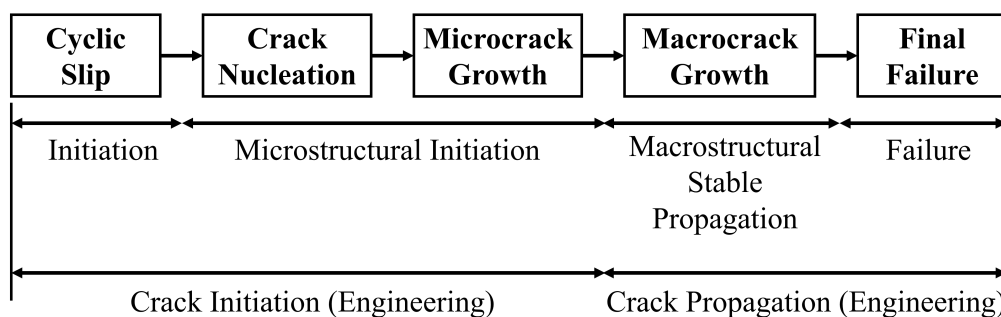


Figure 2.2: Different phases of the fatigue damage, adapted from [2]

The repeated failures involving metallic components in various industries, even in the absence of a thorough understanding of the fatigue phenomena and related regimes, prompted pertinent inquiries into the causes of such unanticipated collapses, leading to more research.

2.3 Fatigue design methods

The prevalence of fatigue-related failures across various industries has led to the establishment of standardized techniques, serving as essential recommendations for structural analysis during the design phase. The European Union's normative procedures were unified by submitting multiple standards that address structural challenges associated with diverse materials, thereby replacing the national guidelines of member states.

Due to the potential need for a large amount of input data for the design, fatigue analysis is typically iterative. This input data includes parameters such as geometry, load history, environmental factors, design criteria, material properties, and manufacturing effects.

The selection of the fatigue life method is another crucial step in the fatigue analysis. This decision ensures the thorough analysis of the fatigue issue. Several methods are currently available for these studies, including the stress-life (S-N) model, the local strain-life (ϵ -N) model, the fatigue crack growth (da/dN - ΔK) model, and the two-stage model that combines the strain-life model and the fatigue crack growth model to incorporate macroscopic crack formation (nucleation) and fatigue crack growth.

Despite its limitations, the stress-life model remains widely applied in numerous engineering applications, as the most common related nominal stresses to the fatigue resistance of components with or without notches. On the other hand, the local strain-life concept establishes a link between the fatigue strength of smooth specimens under controlled tension and the strain at a notch. Implementing the fatigue crack development method and integrating the crack growth equation both require a good understanding of fracture mechanics in order to determine the cycles needed for crack grow from one length to another or to reach a critical length associated with fracture [16].

To enhance comprehension of various fatigue methods, the subsequent sections will analyse a selection of these methods.

2.3.1 Stress-life (S-N) method

The process of fatigue development is influenced by the local response magnitude and the number of cycles required for significant crack growth. In the high cycle fatigue regime (HCF), where fatigue lives are long and stresses and strains mostly remain in the elastic range, stress-life approaches have been employed. In general, these approaches do not differentiate between crack initiation and propagation, and the overall fatigue life is evaluated. However, certain local approaches focus solely on crack initiation, particularly those based on effective notch stresses.

Stress-life methods establish a connection between the stress range and fatigue failure, expressed in terms of number of cycles, which is typically presented in the form of S-N curves. These curves are derived from testing specimens until perceptible cracking occurs under constant amplitude stress ranges, $\Delta\sigma$. The S-N curves provide valuable insights into the relationship between stress levels and fatigue life, aiding in the assessment and prediction of fatigue failure for different materials and structures [17].

The stress-life method encompasses various approaches, including the nominal stress method, the hot-spot stress method, and the effective notch method [18, 19, 17].

Figure 2.3 exhibits the alternating stress σ_a , mean stress σ_m , maximum stress σ_{max} , minimum stress σ_{min} and stress range $\Delta\sigma$, superimposed on the constant amplitude stress versus time curve. The mentioned stresses are related to each other by the equations 2.1, 2.2, 2.3 and 2.4, where the tensile or compressive stresses are taken algebraically as positive or negative, correspondingly.

$$\sigma_a = \frac{\Delta\sigma}{2} = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2.1)$$

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (2.2)$$

$$\sigma_{max} = \sigma_m + \sigma_a \quad (2.3)$$

$$\sigma_{min} = \sigma_m - \sigma_a \quad (2.4)$$

The stress ratio R , and the alternating ratio A are defined by the equations 2.5 and 2.6.

$$A = \frac{\sigma_a}{\sigma_m} \quad (2.5)$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2.6)$$

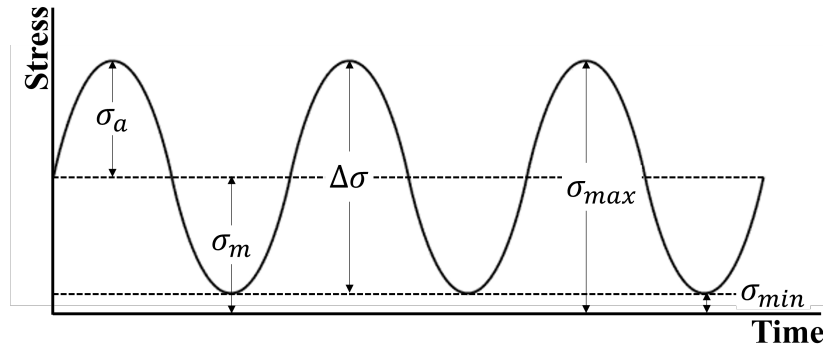


Figure 2.3: Stress-Strain life approach: nomenclature, adapted from [20]

Structures typically do not experience stresses with consistent amplitude due to the randomness in both the applied loads and the structural response. As depicted in figure 2.4, fatigue analysis is typically conducted by breaking down variable time-dependent loads into multiple sets of constant amplitude stresses. This segmentation is made possible through the utilization of a cycle counting algorithm. The most straightforward approach to implement this method involve utilizing the rainflow counting technique, which is a method to determine the number of fatigue cycles present in a load-time history [21], as it is represented in figure 2.4 [22]. Each set is characterized by a mean stress, a stress range and a corresponding number of cycles associated with it. This approach allows for a more manageable and systematic analysis of fatigue behavior under fluctuation loads.

Upon examining Figure 2.4, it is crucial to introduce Miner's law. This law allows establishing a failure criterion for a given fatigue phenomenon. It is mathematically represented by the equation 2.7, where D denotes the accumulated fatigue damage, k represents the number of blocks, n_i signifies the number of constant amplitude cycles applied during block i characterized by a specific strain/stress range, and N_i represents the number of cycles until failure resulting solely from the application of the corresponding loading conditions [23].

$$D = \sum_{i=1}^k \frac{n_i}{N_i} \quad (2.7)$$

Delving deeper into the nominal stress method, this widely employed global technique involves assessing ranges of nominal stresses associated with a specific fatigue resistance thresh-

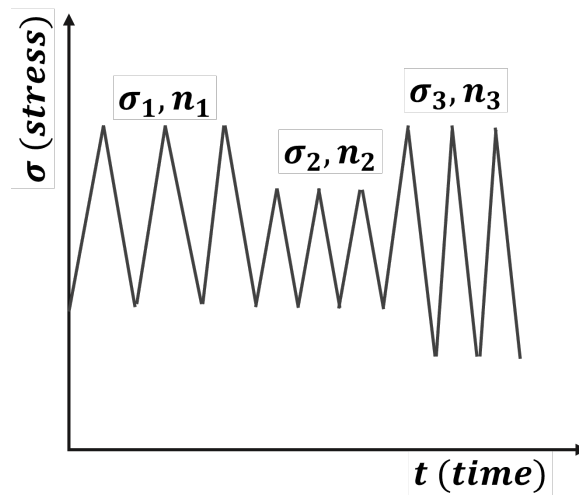


Figure 2.4: Organising variable amplitude stresses according to the amplitude of the stress, adapted from [22]

old. Continuing with this methodology, the S-N curves take into account the effects of localized stress concentrations. This enables the performance of a structural analysis utilizing only nominal stresses, thus directing attention solely towards the internal forces that affect the structural component while aligning with its fatigue strength. The requisite stress values can be derived using principles from linear elastic structural mechanics for simpler components or through the finite element method for relatively intricate structures.

S-N curves, which fully model the resistance side in the nominal stress methods, are proposed in standards and guidelines governing fatigue assessment for bridges, tailored to distinct details and loading conditions. However, this methodology proves to be less suitable when examining connections not geometrically linked to classified details or when disparities arise in applied loads or material properties [17, 24].

Despite the extensive adoption of the nominal stress method, several pertinent limitations come into play:

- **Experimental Testing Challenges:** Developing new S-N curves through experimental tests is ideally conducted on full-scale components. However, this approach often proves expensive, time-intensive, and incongruent with the overall timelines of design and construction phases;
- **Dispersed Data Results:** The data obtained from experimental tests to establish required S-N curves frequently displays a high degree of scatter. Consequently, this often leads to the adoption of exceedingly conservative $\Delta\sigma - N$ ratios in most instances;
- **Limited Insight into Damage Evolution:** The utilization of S-N curves solely allows the determination of failure modes associated with overall damage. It fails to incorporate the nuanced influence of damage progression over time and successive loading cycles;

- **Inadequate Fatigue Crack Insight:** Following routine inspection procedures, the discovery of fatigue cracks is plausible. However, S-N curves do not offer insights into the inherent level of structural risk associated with these cracks.

Given these factors, for critical fatigue-prone sections of steel bridges, the fatigue life predictions based on nominal stresses might yield results that are excessively cautious, unreliable, or even unfeasible to assess. This holds true particularly when the applicability of existing S-N curves remains unchecked against the prevailing conditions.

The S-N curve portrays the connection between the zero-mean characteristic stress and fatigue life. This curves cannot take the average stress into account when it is variable and important, for example, in riveted details. To address this, several commonly employed formulas correct for mean stress effects. These include Goodman's linear model (equation 2.8), Gerber's parabolic model (equation 2.9), and Morrow's model (equation 2.10), as depicted in figure 2.5, where σ_a is the alternating stress, σ_{f0} is the fatigue limit for $\sigma_m = 0$ and f_u is the fatigue strength.

$$\sigma_a = \sigma_{f0} \left(1 - \frac{\sigma_m}{f_u}\right) \quad (2.8)$$

$$\sigma_a = \sigma_{f0} \left[1 - \left(\frac{\sigma_m}{f_u}\right)^2\right] \quad (2.9)$$

$$\sigma_a = \sigma_{f0} \left(1 - \frac{\sigma_m}{\sigma_f}\right) \quad (2.10)$$

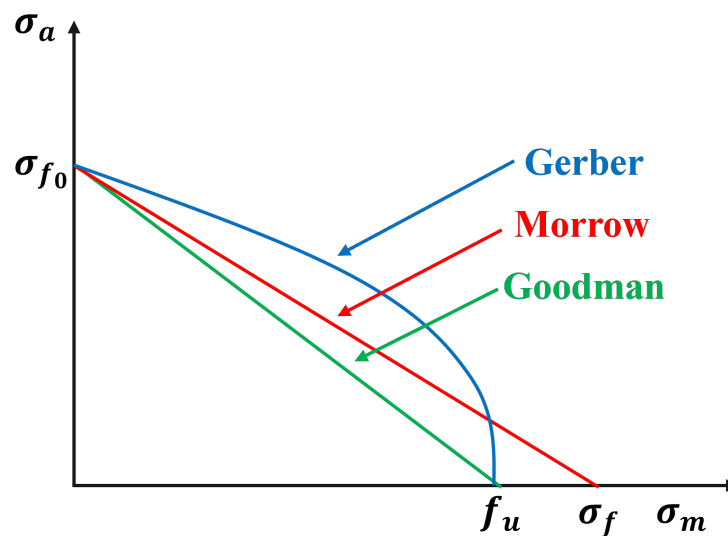


Figure 2.5: Mean stress correction on fatigue limit, adapted from [16]

The accuracy of this method relies on the availability of a catalog of S-N curves, which inherently involves a certain degree of approximation between the actual detail and the chosen resistance limit. Consequently, it is worth noting that the method may not accurately capture the local intricacies of the load transfer mechanism, thereby influencing the results and their representativeness. Often, the mentioned approach tends to be conservative, overly restricting the remaining lifespan of existing structures [2]. Additionally, it can be considered unsafe in specific scenarios, such as double shear connections [25].

Hence, it becomes imperative to explore alternative avenues to enhance analysis reliability. Local methods can be considered as a viable option if the challenges associated with multiple scales linked to large structures can be overcome. This is because the dimensions of these structures typically span kilometers or meters, while the fatigue-prone areas are confined to the scale of square millimeters or even smaller.

2.3.2 Strain-Life (ϵ -N) method

The strain-based approaches were developed with the purpose of analyzing fatigue issues mainly related to relatively short fatigue lifetimes. This technique facilitates the assessment of fatigue strength and service life connected to the crack initiation process at the notch root when the magnitude of strain ranges is compatible with the elastoplastic regime. The strain-life approach offers the advantage that, when considering plastic behavior, measuring or estimating strains is generally more meaningful than stresses. However, this method poses challenges when applied to intricate structures like bridges, as it entails considering numerous factors that influence its application [26].

The foundation of this method is the assumption that the mechanical behavior of the material at the notch root, in terms of local elastoplastic deformation, local damage, and crack initiation, is comparable to the response of small-scale unnotched specimen subjected to axial loading. Specifically, a comparison can be made between the elastoplastic stresses and strains at the notch root of the examined structural detail and the strain S-N curve of the material assessed in an unnotched specimen, figure 2.6.

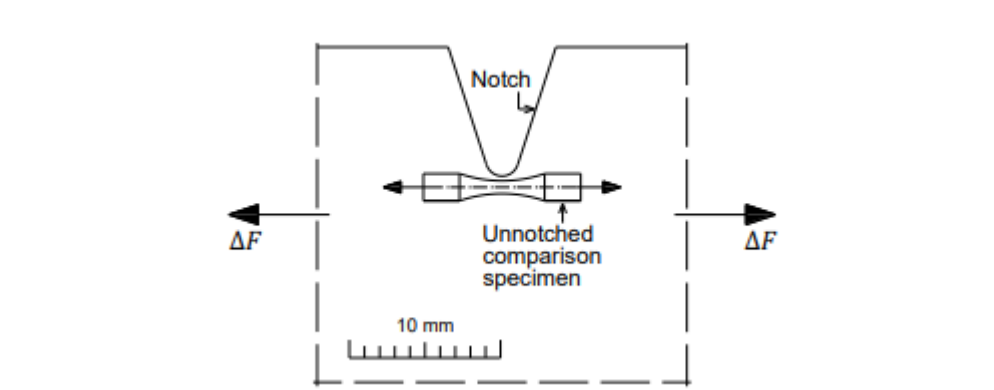


Figure 2.6: Strain-life notch strain approach [27]

As is well-known, plastic deformation results in permanent changes in the material even after unloading, as depicted in figure 2.7. In this context, σ represents the stress, E denotes Young's modulus, ε_e represents elastic deformation, and ε_p is the plastic deformation.

The mathematical equation 2.11 describes this behavior relating the true stress, represented by σ , to the true plastic strain, denoted as ε_p . This relationship is characterized by the strength coefficient, K , and the strain hardening coefficient, n .

$$\sigma = K(\varepsilon_p)^n \quad (2.11)$$

The strain hardening coefficient, n , typically ranges between 0.05 and 0.25, serving as an indicator of the material's resistance to deformation. As plastic deformation advances, the material gradually becomes more resistant due to the phenomenon of strain hardening, which consequently plays a pivotal role in understanding the material's response to plastic deformation.

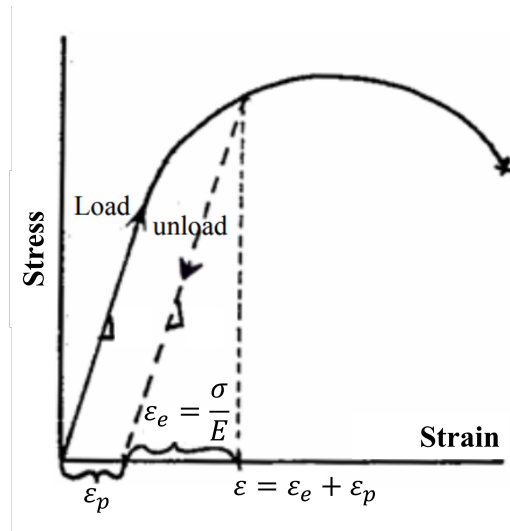


Figure 2.7: Stress-strain curve related with plastic deformation, adapted from [28]

When the notch strains, denoted as ε , are not measured, they are typically unknown and can be calculated using the notch stress results, represented as σ , by considering the macrostructural support formula proposed by Neuber [29] and/or Glinka [30, 31], introduced the cyclic stress-strain curve established by Ramberg and Osgood [32], wherein E represents the Young's modulus, K' and n' are the cyclic strain hardening coefficient and exponent. The mentioned formulas are expressed in equation 2.12, 2.13 and 2.14, respectively.

$$\frac{(k_t \Delta \sigma_{nom})^2}{E} = \frac{\Delta \sigma^2}{E} + 2 \Delta \sigma \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}} \quad (2.12)$$

$$\frac{(k_t \Delta \sigma_{\text{nom}})^2}{E} = \frac{\Delta \sigma^2}{E} + \frac{4 \Delta \sigma}{n' + 1} \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}} \quad (2.13)$$

$$\Delta \varepsilon = \frac{\Delta \sigma}{E} + 2 \left(\frac{\Delta \sigma}{2K'} \right)^{\frac{1}{n'}} \quad (2.14)$$

A counting cycles technique should be applied after establishing the strain-time history at notch root in order to assess the damage contribution of each cycle. Subsequently, a linear damage accumulation approach can be applied. Moreover, certain standard specifications provide strain S-N curves that can be used to determine the number of cycles required for crack initiation to occur.

2.3.3 Fracture Mechanics and fatigue crack propagation law

Fracture mechanics has found applications in various domains to investigate fatigue crack propagation issues, and effective results have been widely validated across numerous engineering industries. By connecting the propagation of an initial crack to the quantity of loading cycles, one can predict the fatigue life for cracked components using concepts from fracture mechanics. This method may be complemented by methods based on stress or strain, with the latter primarily utilized to assessing fatigue crack initiation.

The stress intensity factor, K , which represents a parameter from the linear elastic fracture mechanics, was first developed by Irwin [33], represented by the following equation 2.15, and can be used to characterise the stress and strain fields around the fracture tip [34].

$$K = Y \cdot \sigma \cdot \sqrt{\pi a} \quad (2.15)$$

The strain energy release rate, G , connected to the crack, according to Irwin [33] and Griffith [35], is related to the idea of stress intensity factor, where, in addition to the already mentioned factors, ν , is the Poisson's ratio.

$$G = \frac{K^2}{E} = \frac{\sigma^2 \pi a}{E} \quad (2.16)$$

$$G = \frac{K^2}{E} (1 - \nu) = (1 - \nu^2) \frac{\sigma^2 \pi a}{E} \quad (2.17)$$

Three distinct pure modes of fracture propagation – mode I, II and III – can be distinguished depending on the loading and how it affects the crack's orientation.

According to the figure 2.8, it is evident that Mode I represents the most severe example and the type of failure most frequent.

For each mode, the stress intensity factor is denoted differently: for Mode I is designated by K_I , for Mode II as K_{II} , and for Mode III as K_{III} .

It is possible to distinguish and relate K_I , K_{II} and K_{III} , to G_I , G_{II} and G_{III} , respectively, using the concepts of stress intensity factor, strain energy release rate, and the different propagation modes. Such quantities may be connected in plain strain as follow:

$$G_I = \frac{K_I^2}{E}(1 - \nu^2) \quad (2.18)$$

$$G_{II} = \frac{K_{II}^2}{E}(1 - \nu^2) \quad (2.19)$$

$$G_{III} = \frac{K_{III}^2}{E}(1 - \nu^2) \quad (2.20)$$

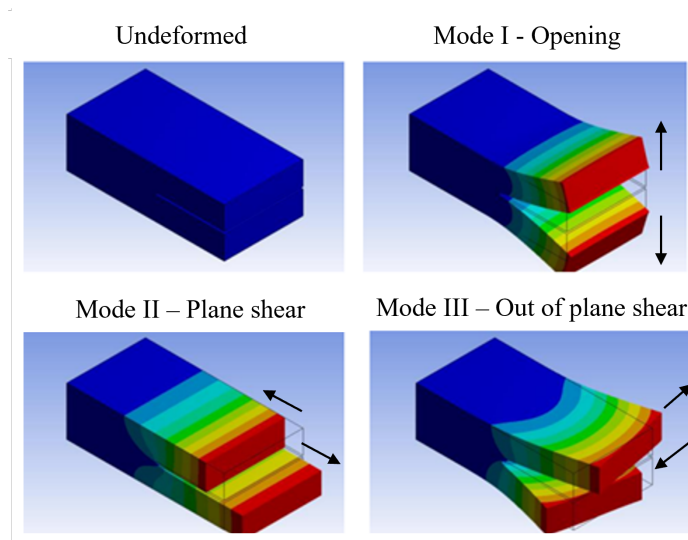


Figure 2.8: Stress intensity modes, adapted from [36]

When the strain energy produced as a result of the fracture extension surpasses the energy required for the subsequent increment, the crack propagates in an unstable manner. In these circumstances, it can be inferred that the fracture has reached its critical length, a_c . The definition of a_c depends on the characteristics of the material, and in mode I, this dependence is determined by the material's toughness, which is assessed using the critical stress intensity factor, K_{Ic} , and the critical energy release rate, G_{Ic} [37].

$$\text{Plane – Stress : } G_I = \frac{K_{IC}^2}{E} = \frac{\sigma_{Ic}^2 \pi a_c}{E} \quad (2.21)$$

$$\text{Plane – Strain : } G_I = (1 - \nu^2) \frac{K_{IC}^2}{E} = (1 - \nu^2) \frac{\sigma_{Ic}^2 \pi a_c}{E} \quad (2.22)$$

For stress intensity factors below the critical value, cracking may start and propagation under cyclic loading circumstances. This process is known as sub-critical growth, and it is a key notion to determine the amount of life still left in components with fractures smaller than the crucial measurement. The increase in the crack dimension, a , per loading cycle, N , for a cracked geometry under cyclic loading in which an acting stress, σ , changes between minimum and maximum values, respectively, σ_{min} and σ_{max} , may be analytically characterized by equation 2.23, where, R is mentioned in the equation 2.6 and $\Delta\sigma$ is mentioned in the equations 2.24 and 2.1.

$$\frac{da}{dN} = f(\Delta\sigma, R, a) \quad (2.23)$$

$$\Delta\sigma = \sigma_{max} - \sigma_{min} \quad (2.24)$$

According to Paris et al. [38], the range of stress intensity factor, $\Delta K = K_{max} - K_{min}$, which correspond to the maximum and minimum stresses, can be used to represent the relation between the loading and the crack propagation rate. As a result, when the applied stress range and the stress ratio are both constant, the only variable that influences the crack propagation rate, da/dN , is ΔK , equation 2.26.

$$\frac{da}{dN} = f(\Delta K) \quad (2.25)$$

A correlation between the crack propagation rate, da/dN , and the stress intensity factor range, ΔK , was discovered after extensive testing. As can be seen in the figure 2.9, the results obtained allowed for the definition of three distinct propagation regimes or areas.

It is also crucial to note that the Paris law has a number of shortcomings that have prompted the creation of more intricate cracking regulations in an effort to accurately portray the recognised propagation regimes, particularly region II, where there is a linear dependence between $\log(\frac{da}{dN})$ and $\log(\Delta K)$ [14]. Importantly, when the fatigue life of the material is primarily influenced by region II, the Paris law can be employed for the calculation of fatigue life.

A task of utmost importance is computing of stress intensity factor time histories, which can be accomplished using a variety of techniques: analytical methods, weighting functions, boundary

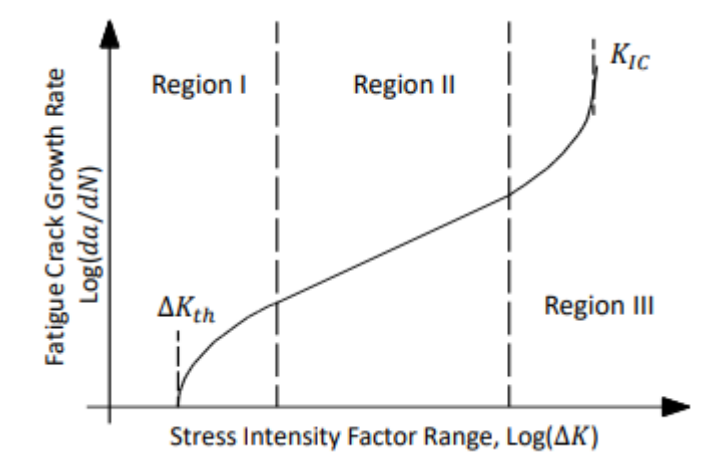


Figure 2.9: Relation between da/dN and ΔK , with permission from [2]

elements, and finite element methods.

Fracture mechanics involves several vital variables, among them being the time-dependent stress intensity factor, denoted as $K(t)$. Once this parameter is determined, it becomes feasible to employ a cycle counting algorithm. Subsequently, Paris' law can be utilized to compute the crack propagation increment [34].

The term fracture toughness is typically attached as a measure of material resistance to extension of a crack. For the purpose of assessing structural integrity, designing damage tolerances, determining fitness-for-service, and analysing residual strength for various engineering components and structures, experimental measurement and standardization of fracture toughness are essential.

The fracture mechanics approach is essentially distinct, due to the fact that it studies how fatigues fractures propagate through a particular material and is more focused on what happens at the propagating crack tips than on loading at a large scale.

Mathematically, the factor K is defined as the product of applied macroscale stress (σ) of the square root of the crack length (a) and a dimensionless constant (C) that depends on the particular fracture mode and geometry of the test specimen [36], equation 2.26.

$$K = C_{f(mode, geometry)} \cdot \sigma \sqrt{a} \quad (2.26)$$

The critical stress intensity factor (K_c) denotes the least amount of stress necessary to cause an already existing crack in a material to propagate and is used to represent the fracture toughness. Since defects can occasionally develop during the manufacturing, production, or use of a material or component, this material attribute becomes crucial. Cracks, voids, metallurgical inclusions, weld flaws, discontinuities in the design, or some combination of these may all be signs of flaws.

The fracture propagation will be instantaneously catastrophic under prescribed-load boundary conditions. Any imperfection that is sufficiently large (length a) to have a stress intensity that may exceed K_c under the loading may immediately fail [39].

2.4 Fatigue phenomenon in railway bridges

As a result of the repeated application of external loading such as traffic on steel bridges, wind for tall buildings, waves on offshore platforms, and temperature changes for turbine engines, structural damage gradually accumulates, leading to fatigue.

The failure mechanism associated with strength and serviceability have received extensive research over time in the engineering professions. However, there is still a lack of knowledge regarding the causes of development and mechanisms of failure for fatigue, one of the most significant types of damage and the main failure modes for steel structures [17]. Figure 2.10 illustrates the fatigue limit state for nonferrous alloys, ferrous alloys, and titanium, comparing stress levels with cycles to failure.

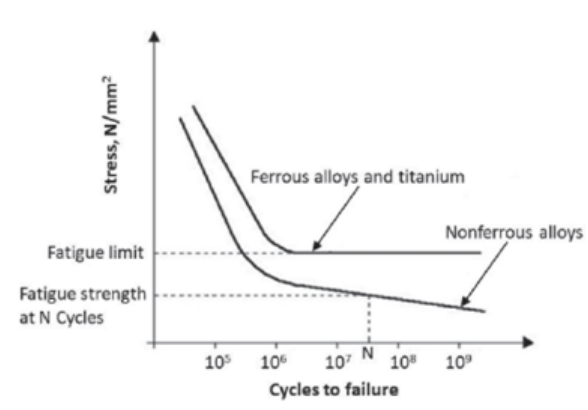


Figure 2.10: S-N curves of metal alloys [40]

Many of the railway bridges in the UK, other areas of Europe, and North America are made of wrought iron and aged steel, and many of them are already more than 100 years old.

These bridges, which were constructed with rivets, prior to standardization and the broad use of design regulations, were created at a time when fatigue was undoubtedly not a factor taken into account in design. Questions about their fatigue performance have been raised as a result of the steadily increasing in axle loads and train frequencies, which they have endured during their service life [41].

Due to active dynamic loadings throughout their service life, metallic bridges, which are significant structures from both an economic and social perspective, are susceptible to fatigue phenomenon, see table 2.1. Such load scenarios are primarily influenced by the type of traffic situation, which is characterized by a large number of moving vehicles traveling at various speeds and producing varying stress time histories with many applied load cycles.

Given the magnitude of the loads, it stands to reason that fatigue damage of railway bridges is more severe than that in highway ones. This may be especially important when freight traffic is frequent.

The three primary categories of metallic bridges - riveted, welded, and bolted - can be broadly classified based on the specific local structural details that are susceptible to fatigue concerns.

As already mentioned, the fatigue phenomenon is a prevalent factor in the gradual loss of structural integrity or eventual collapse, and because it is the main cause of serious damage in a variety of steel structure type.

After analysing the table 2.1, it can be seen that one of the main reasons for damage to structures is fatigue, with bridges being the most affected. It is also expected that older steel bridges will have a greater response to fatigue phenomena, due to older metal materials and their construction.

Table 2.1: Types of damages caused in several steel structures [42]

Damage cause	Total		Buildings		Bridges		Conveyors	
	Nº	%	Nº	%	Nº	%	Nº	%
Static strength	161	29.7	102	33.6	19	14.8	40	36.0
Stability (local or global)	87	16.0	62	20.4	11	8.6	14	12.6
Fatigue	92	16.9	8	2.6	49	38.3	35	31.5
Rigid body movement	44	8.1	25	8.2	2	1.6	17	15.3
Elastic deformation	15	2.8	14	4.6	1	0.8	0	0
Brittle fracture	15	2.8	9	3.0	5	3.9	1	0.9
Environment	101	18.6	59	19.4	41	32.0	1	0.9
Thermal loads	23	4.2	23	7.6	0	0	0	0
Others	5	0.9	2	0.7	0	0	3	2.7
Sum	543	100	304	100	128	100	111	100

2.4.1 Riveted metallic bridges

Due to the historical significance of riveting as the primary connecting method used in the construction of iron and steel structures, riveted structures were extensively employed since the early 1860s. Before the advent of welding methods and bolted joints, riveting was the main technology utilized in construction. Today, many riveted structures require maintenance and potential strengthening due to the passage of time and changing structural demands [43].

The first half of the 20th century saw the construction of a substantial portion of the European railway bridges. In Portugal, a large number of historic bridges have endured and are currently in use. This is primarily due to historical factors and financial constraints. As a result of Portugal's Second World War neutrality and the country's limited financial resources, ageing bridges were repaired and retrofitted rather than being completely replaced. According to data gathered from the Portuguese railway administration REFER, the number and kind of railway bridges in Portugal are shown in table 2.2. Several studies indicate that a significant portion of metallic railway bridges are at least 100 years old.

The assessment of a bridge's remaining fatigue life is garnering the attention of railway authorities as an increasing number of bridges approach the end of their theoretical lifespan. Moreover, the behavior of construction materials under fatigue conditions remains uncertain, especially concerning wrought iron and older steels, which exhibit inherent heterogeneity, making their fatigue study more challenging. Additionally, the lack of knowledge regarding their loading histories further complicates the evaluation of their structural integrity.

Table 2.2: Portuguese railway, number and type [22]

	Type of railway gauges / type of bridge								Total
	Narrow gauge				Broad gauge				
	Masonry	Concrete	Metallic	Composite	Masonry	Concrete	Metallic	Composite	
Deactivated	89	13	29	-	153	31	40	1	356
Operational	29	10	2	1	547	870	489	62	2010
Total	118	23	31	1	700	901	529	63	2366

In their original form, rivets comprise a smooth cylindrical shaft and what is commonly known as the "factory head" on one of the ends, as illustrated in figure 2.11. Once the rivet is inserted, the end of the shaft is bent, resulting in the formation of the second head known as the "shop head." During this process, the shaft expands, generating friction and contact forces that firmly fasten the rivet to the plates. According the figure 2.11, A – factory head diameter; H – factory head length; L – shaft length and D – shaft diameter.

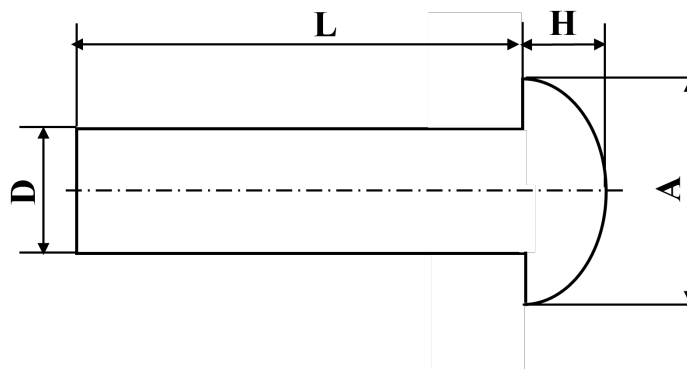


Figure 2.11: Rivet geometry, adapted from [22]

During the 19th century, the riveting operation was manually performed through punching, leading to poor quality riveted joints mainly due to hand-hammered rivets, figure 2.12. However, in the early 20th century, railway authorities took significant action in response to numerous rivet failures and fatigue cracking occurring near rivet hole edges [44]. New norms and standards were adopted, encompassing aspects such as the minimum distance between rivets, the required type of riveting machinery, installation procedures, and guidelines for drilling rivet holes. These measures were implemented to improve the overall quality and reliability of riveted structures [45].

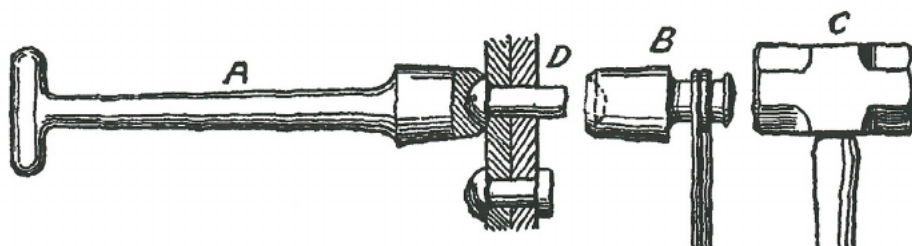


Figure 2.12: Process of fastening rivet on the 19th century [45]

The preservation of historically significant constructions has resulted in the continued use of the outdated riveting process, often requiring the replacement of loose or missing rivets. Both railway and motorway administrations, along with the owners of such structures, tend to prefer the original riveting method to maintain the authentic appearance of these structures.

Nevertheless, rivets exhibit limitations in terms of their capacity when larger diameters and/or lengths of the shank are needed. Moreover, disassembling structural elements that have been riveted becomes more challenging. Rivets can also increase the weight of structures and weaken them due to the presence of additional rivet holes, which may result in increased labor costs and execution difficulties. As a result, modern welding and high strength prestressed bolts have gradually replaced rivets in many applications due to their superior performance and practicality [44, 46].

2.4.2 Example of the fatigue phenomenon in metallic bridges

Since the late 19th century to the present, it has been noted that a number of bridges experienced a loss of structural integrity or a total collapse while they were still in use, without exhibiting earlier and more pertinent signs of degradation. Understanding the causes of some of these incidents has been associated with awareness of the phenomenon of fatigue and its contributing factors.

One such example is the Silver Bridge, constructed between 1927 and 1928, and opened to traffic to connect Point Pleasant, West Virginia, and Gallipolis, Ohio, was an eyebar-chain suspension bridge, figure 2.13.



Figure 2.13: Silver bridge [47]

On December 15, 1967, the bridge suddenly collapsed during the evening rush hour, after almost forty years in service. According to the National Transportation Safety Board (1970), the bridge caved in due to the spread of a crack at one of the suspension system's eyebars on the northern side. Stress corrosion and corrosion fatigue together caused the localized fracture.

Comparing the fractured eyebar with a schematic representation of the undamaged connection in figure 2.14, the crack propagated through the fatigue-critical detail leading to an ultimate failure mode, due to the constant dynamic loadings. As the primary structural system was not planned with any redundancy, once the local failure occurred, the existing load-carrying path was disrupted, making it impossible to achieve structural balance.

The side span on the Ohio side began to collapse near the Ohio tower, starting with the first joint of the eyebar west of the Ohio tower came apart. As result of the separation of the joint and the failure of the eyebar, the Ohio tower fell eastward, causing the West Virginia tower to fall eastward and downstream, figure 2.15. The middle portion of the center span broke in three parts and turned over upstream. This quick sequence of events had consequently forty-six people casualties.

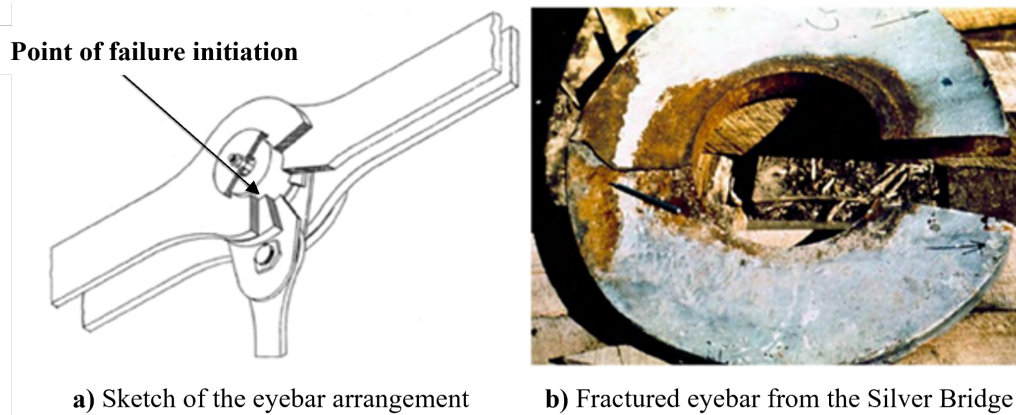


Figure 2.14: Silver bridge, adapted from [48, 49]

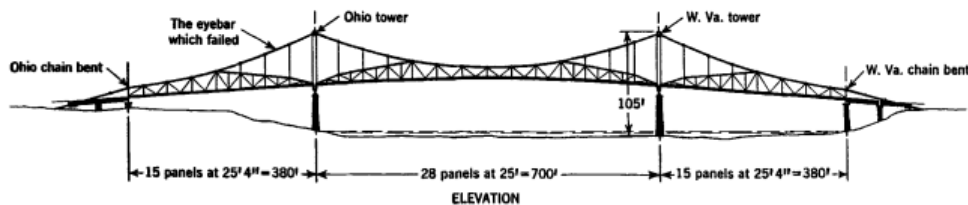


Figure 2.15: Silver bridge overview [48, 47]



Figure 2.16: Silver bridge after collapse [50]

After the collapse of the bridge, figure 2.16, three task forces were appointed with specific assignments. The first step was to assess the efficacy of the current bridge inspection procedures. The second was to make plans for an early bridge replacement. Under the direction of the National

Transportation Safety Board, and the third task force had the responsibility of identifying the root causes of failure. Following these analyses, it was verified that the structure had not been properly monitored and maintained [47, 51].

2.5 Improving fatigue life in metallic bridges

A sizable component of the infrastructure stock in many nations is made up of metallic railway bridges of all kinds. In spite of that, over time, the aging of these structures and the increasing traffic loads have led to structural fatigue, becoming a growing concern.

In some cases, replacement of structural components linked to important details is not always feasible or the most cost-effective course of action. It might have adverse effects on the regular operation of a particular bridge or exceed the scope of repairs or strengthening permitted. Therefore, a number of measures may be used to enhance the ability of people or subsystems that have been designated as vital to function while fatigued.

Some common repairs and strengthening techniques for metallic bridges have been employed, with an emphasis on local interventions, which are worth highlighting. Starting by enumerating the techniques, holes can be drilled at the crack front, figure 2.17, which occurs when the critical area's stress field is changed resulting in reduced stress intensity factor ranges ΔK . It can effectively address induced fatigue distortion cracking due to the temporary reduction in stiffness and subsequent reduction in secondary moments. However, it should be noted that this corrective approach may not be suitable for highly stressed locations, as the hole's reduction in net-section could lead to structural issues with the ultimate resistance. Additionally, for larger fatigue cracks, this strategy is inappropriate, as a new fracture could initiate from a fault at the circular hole.

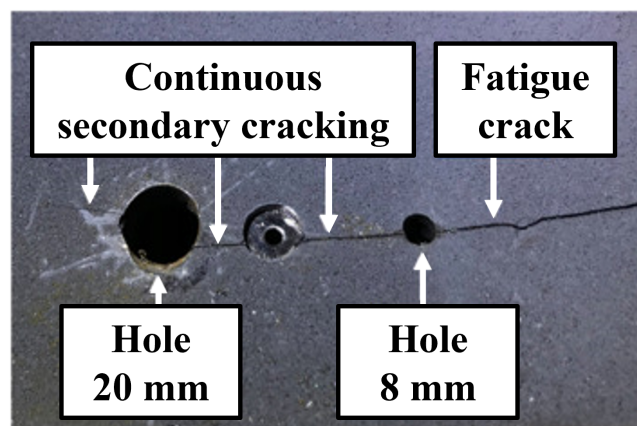


Figure 2.17: Fatigue crack, adapted from [52]

Other strengthening approach may be that based in cover plates technique which is used to enhance the cross-sectional area by covering the fracture with plates made of various materials to lower the stress range. This traditional method entails fixing steel cover plates to the fractured metallic element with prestressed high strength bolts, which improves the net-section locally. Although the clamping stress created by the bolts should reduce the importance of any notches that

may result from the drilling operation, such a solution shouldn't be used in high-stress locations. The cover plate can only be positioned on flat fastener-free surfaces in riveted or bolted connections.

In the repairing cuts technique, instead of drilling holes at the fracture front, cuts may be made at a crucial detail to reduce the local stress field. The properties of the connections may change depending on the direction and the placement of the patch cuts, which may alter the local structural behavior. Particularly for highly pressured members, new concerns with fatigue damage or ultimate resistance may emerge and necessitate careful assessment.

Another alternative is removing rivets or loosening bolts. As part of the repairing cuts, rivets may be removed or bolts loosened at the respective critical elements, changing how connected members will respond locally. To retain the mechanism of loading transference in case of rivets, some mechanical fasteners may be removed and others replaced with high strength bolts. Additionally, specifics related to bracing systems connected to the primary structural elements, such as those, may find releasing bolts to be equally helpful. The elements acting as bracing should be inactive in service limit states to minimize the secondary effects on the major members, but in the ultimate limit state, the corresponding structural reaction can be mobilized. If necessary, removing rivets and loosening bolts can be done together.

After cold working with a mandrel, the diameter of the rivet or bolt's hole is expanded. This causes plastic deformations that produce residual compressive stresses adjacent to the hole, increasing the detail's fatigue resistance. When used in conjunction with other techniques, this procedure called cold expansion, enables enhancing the initial fatigue resistance and can be utilized to stop fatigue cracks that have already begun to propagate. Naturally, a bolt should be used in place of mechanical fastener in riveted connections.

When used together, the majority of the strategies mentioned are more effective at addressing problems. However, Bassetti et al. [53] state that when flaws are found early, other repairs techniques that are not suitable for use with old metallic materials, such as old wrought iron and old mild steel, may be employed. Alternative techniques include gas tungsten arc remelting (TIG), which involves remelting the metal to remove flaws and tiny fissures with length less than 3 mm. This method was created for modern steels and welded buildings. The alternative option is the gouging of crack with an air-arc, filling the gouged area with weld metal. This method is used to regulate the crack dimensions and should be combined with a corrective action that lowers the stress field and fatigue stress range in the cracked area.

When examining the conventional repairing and strengthening techniques that have been described, it can be said that the main strategy revolves around the localized reduction of the magnitude of the stress fields close to the detected critical zones as well as the stress intensity factor in the situations where cracks are actively spreading. The efficiency of those corrective actions depends on inspections for the quick identification of fatigue cracks and techniques to forecast permissible directions of propagation [10, 2].

2.6 Reinforcement in metallic components with Carbon Fibre-Reinforced Polymers (CFRP)

Investigation of engineering components, machine or structures breakdowns now predominantly rely on failure analysis. For designers, engineers, and manufacturers, the expense of repairs and operational failures serve as a warning sign about whether or not to keep old machines or structures in service, if they are worth fixing, or whether new machines or component designs are required. Among the most severe types of damage is fatigue, yet accurately analyzing or predicting the extent of damage and remaining fatigue life persist challenging. Evaluating fatigue damage and predicting life using deterministic or probabilistic approaches have been the subjects of numerous studies.

In the present context, it's critical to reduce the phenomena of fatigue for this reason. This has been researched more and more over the years in an effort to find solutions and strategies to lessen it. Utilizing materials with greater fatigue resistance, such as high-strength alloys or composites, is one strategy. Another strategy is to design components with smooth surfaces and stay away from stress concentrations and sharp corners that could lead to fracture formation. Additionally, it's critical to maintain and examine mechanical system properly to find any signs of wear and tear before they result in failure. Regular components inspections, load monitoring are a few examples of this [17].

This study primarily addresses fatigue-related damages in railway metal bridges, with a focus on exploring strategies to mitigate the occurrence of this phenomenon, in this scenario, employing CFRP composites.

By definition a composite is a material which is produced by two or more different constituent materials with significantly different physical or chemical properties. Typically, the constituents are mixed in a way that creates a material having unique qualities from each of its constituent parts. Due to their superior qualities to conventional engineering materials and be tailored to suit specific requirements, composite materials are frequently employed in innovative structures in the aerospace, automotive, marine, petrochemical, and many other industries.

Notwithstanding, it is important to mention that composites are also delicate and prone to damage from a variety of causes, both during initial production and when in use, in spite of these advantageous physical characteristics. A thin-walled composite construction can be significantly impacted by even seemingly insignificant impact events, such a tool drops during assembly. As damage can never be completely prevented, composite structures should be made to be safe to use even when they have defects [54].

Carbon fibre reinforced polymers (CFRP) is a composite material made of carbon fibres, which offer strength, stiffness, and load carrying ability, and a polymer matrix. This polymer is garnering increased interest in the realm of engineering materials, principally due to their high strength to weight ratio. They outperform a variety of common technical materials, including polymers, metals/metal alloys, and foams, in terms of stiffness and strength qualities relative to weight (specific

stiffness and strength, respectively). The figure 2.18 shows a diagram, which allows for comparison of the stiffness and strength of certain materials.

Additionally, CFRP exhibits a wide range of qualities that make it suitable for various applications. It can be manufactured in diverse forms, tailored for specific uses, and undergoes distinct manufacturing processes [55].

Several studies indicate that the fatigue resistance of CFRP relies significantly on the inherent composite system, encompassing factors such as the fiber and matrix resin types, lay-up sequence, presence of residual stresses, and defects at the fiber/matrix interface [56, 57]. Each of the aforementioned factors exerts a discernible impact on the process of fatigue damage, encompassing crack initiation and propagation, subsequently altering the ultimate fatigue life and mode of failure. Notable manifestations of fatigue damage encompass fiber breakage, cracking within the resin matrix, debonding between fiber and resin, and delamination [58]. When reinforced fibers possess heightened stiffness, the occurrence of matrix cracking can be delayed [25]. This outcome arises from the capability of high-strength and stiffness fibers to withstand elevated loads, thereby constraining the strain experienced by CFRP and consequently mitigating matrix resin cracking.

However, the fatigue behaviour of composite materials and structures is complex, as they degrade through various damage mechanisms, including transverse cracking, fibre-matrix debonding, and fibre breaking. The occurrence of matrix cracking can be significantly delayed if reinforced with high-stiffness materials like carbon, while fiber fracture heavily depends on fiber strength.

In composites, the fatigue performance is influenced by the composite system itself, particularly by the fibre and matrix properties, lay-up sequence, residual stresses resulting from the manufacturing process or due to endured by the material, ply orientation, the fibre/matrix fractions, and environmental factors affecting the composite components.

As mentioned earlier, the use of CFRP is becoming more widespread in a number of industrial fields, including building transportation, and renewable energy. Nevertheless, environmental variables, which may be more or less severe depending on where it is used, will have an impact on its fatigue durability [55].

Metallic structures are crucial in construction, and as the service load on metallic structures, such as bridges, increases, problems become more severe, necessitating their repair and rehabilitation. In general, replacing a steel structure is much more expensive and time-consuming than repairing or adapting one [11, 59].

Bridges are subjected to repeated cyclic stresses, leading to an increase in wear-related issues. Due to their ability to be customized to have exceptional mechanical, thermal, physical, and electrical qualities, composites have grown in popularity over the past 50 years.

The utilization of advanced composite materials in bridge construction started gaining prominence during the period between 1970 and 1980. This emergence was attributed to their advantageous qualities, including a high strength-to-weight ratio and exceptional resistance to corrosion. These attributes played a pivotal role in generating interest in these materials for the purpose of repairing and rehabilitating bridges, encompassing not only the superstructures but also the critical

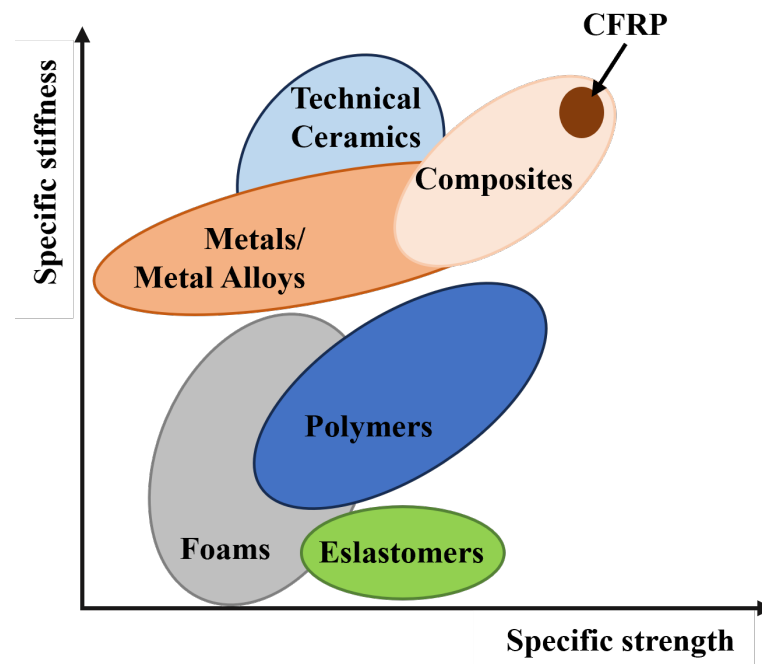
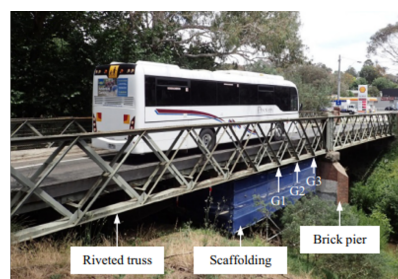


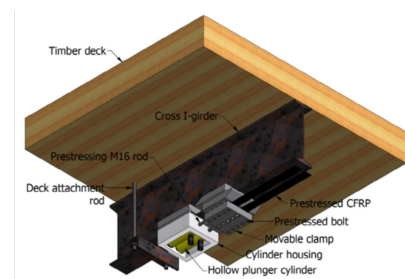
Figure 2.18: Diagram for comparison of the stiffness and strength of different materials, adapted from [55]

components like bridges decks. While numerous studies have been conducted pertaining to bridge repair, it is apparent that a greater emphasis has been placed on applying composites in concrete bridges rather than metal bridges. Nonetheless, there is a growing inclination towards employing this form of reinforcement in metal bridges as well. This trend can be attributed to the fact that these reinforcements can be externally applied and are comparably easier to install [59].

While CFRPs are infrequently employed in steel bridges, they are progressively becoming the preferred composite material for various practical applications. These include reinforcing a 19th-century metallic roadway bridge with nonprestressed bonded and prestressed unbonded CFRP plates [60], as well as external applications like prestressed cables [61], which can alter the distribution of global forces.



a) Diamond Creek Bridge under daily traffic, Melbourne, Australia, December 2017 (G1 to G3 are the strengthened cross-girders)



b) 3D schematic view of the system

Figure 2.19: Process of fastening rivet on the 19th century [60]

Figure 2.19 depicts a 19th-century metal road bridge in (a), along with a 3D representation of the system where Carbon Fiber Reinforced Polymer (CFRP) is applied in (b). The article referenced as [60] focuses on the reinforcement of a 122-year-old metallic road bridge using CFRP plates, without prestressing.

Laboratory tests were conducted to characterize the mechanical properties and confirm the strength of the connection between CFRP and steel. It was discovered that due to the disparity in thermal expansion coefficients between steel and CFRP, daily temperature fluctuations could induce significant thermal stress cycles in the CFRP plates, even without prestressing.

Following a series of analyses, it was determined that the placement of the CFRP reinforcements did not result in any loss of prestress in any of the CFRP plates applied. This finding ensures the reliability and durability of the developed system [60].

2.6.1 Anisotropic Elasticity

Elastic anisotropy refers to materials behaviour when young's modulus, poisson's ratio, and shear modulus, differ depending on the direction of the applied force or deformation. In other words, the material shows varying degrees of elastic behaviour depending on the direction.

There are several materials, such as wood, composites, and various biological materials, that cannot be accurately modeled as isotropic despite fitting the linear elastic model. These materials exhibit distinct mechanical characteristics in different directions and are referred to as anisotropic materials, as their properties depend on direction.

Describing completely anisotropic materials is challenging due to the abundance of elastic constants they possess. However, many partially anisotropic materials still exhibit some material symmetries.

A substance that contains three orthogonal planes of microstructural symmetry is said to be orthotropic. The figure 2.20 a) displays a sample of glass-fibre composite material, which is made up of tens of thousands of extremely long, thin glass fibres bundled together in oval-shaped bundles and enclosed in a plastic binder material. The continuum model is shown in the figure 2.20 b). Each point in the continuum model can be traversed through by three symmetry planes that are mutually perpendicular. The material directions refer to the x, y and z axes that form these planes. The number of independent elastic constants is decreased by the material symmetry present in the orthotropic material.

Transversely isotropic materials have a single material direction and exhibit isotropic behavior in the plane orthogonal to fibers direction. Figure 2.21 shows a glass-fibre composite material with aligned fibres once more, however this time the cross-sectional forms of the fibres are round. The material is isotropic in any plane parallel to the x-y plane, with z being the characteristic material direction. All directions that are transverse to the direction of the fibres have the same material properties. The number of distinct elastic constants is further diminished by this added symmetry over that provided by the orthotropic material.

Any substance whose response is unaffected by direction is said to isotropic and it's the contrair of anisotropy [62].

Equation 2.27, represents the most general form of Hooke's Law for linear elastic materials and it is called as the stiffness matrix. In this formulation, each stress component depends linearly on all strain components. The constants $C_{i,j}$ in the equation represent material properties known as stiffness constants.

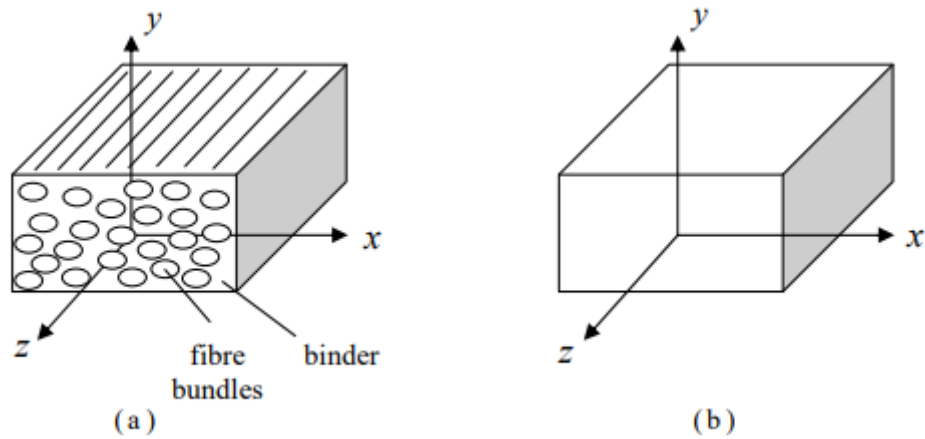


Figure 2.20: An orthotropic material where (a) is microstructural detail and (b) is the continuum model [62]

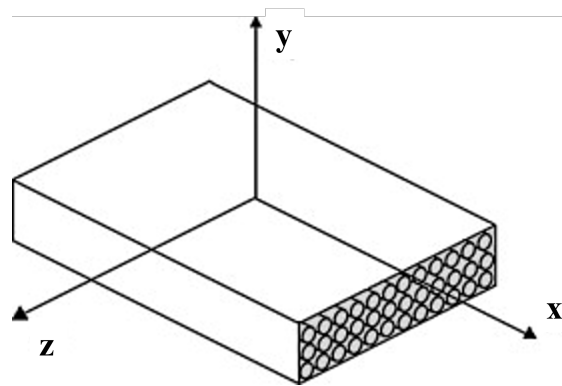


Figure 2.21: Transverse isotropic material, adapted from [63]

$$\begin{bmatrix} \sigma_1 = \sigma_{xx} \\ \sigma_2 = \sigma_{yy} \\ \sigma_3 = \sigma_{zz} \\ \sigma_4 = \sigma_{yz} \\ \sigma_5 = \sigma_{xz} \\ \sigma_6 = \sigma_{xy} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} \\ C_{21} & C_{22} & C_{23} & C_{24} & C_{25} & C_{26} \\ C_{31} & C_{32} & C_{33} & C_{34} & C_{35} & C_{36} \\ C_{41} & C_{42} & C_{43} & C_{44} & C_{45} & C_{46} \\ C_{51} & C_{52} & C_{53} & C_{54} & C_{55} & C_{56} \\ C_{61} & C_{62} & C_{63} & C_{64} & C_{65} & C_{66} \end{bmatrix} \begin{bmatrix} \epsilon_1 = \epsilon_{xx} \\ \epsilon_2 = \epsilon_{yy} \\ \epsilon_3 = \epsilon_{zz} \\ \epsilon_4 = \epsilon_{yz} \\ \epsilon_5 = \epsilon_{xz} \\ \epsilon_6 = \epsilon_{xy} \end{bmatrix} \quad (2.27)$$

As previously mentioned, carbon fiber composites constitute a significant class of materials,

recognized for their high tensile strength, elevated modulus, and low weight. To enhance the effective structural design of composites and ensure robust structural integrity, it becomes imperative to possess a profound understanding of the elastic properties intrinsic to individual carbon fibers, alongside the ability to foresee their mechanical responses accurately.

Carbon fibers are commonly classified into four distinct types based on their strength characteristics: intermediate modulus (IM), high modulus (HM), ultra-high modulus (UHM), and ultra-high modulus with high resistance (HR) [64].

To undertake the forthcoming study, aimed at assessing the performances of CFRP patches to reinforce metallic bridges in real-world applications, certain challenges emerged during the numerical modeling phase. One of the primary difficulties revolved around selecting the appropriate modulus of elasticity suitable for the specific application. To navigate this predicament, our approach involved a systematic evaluation of various modulus of elasticity values, aimed at identifying the optimal fit for achieving the most favorable outcomes.

As previously mentioned, the subsequent section directs its focus toward the analysis of a simplified example. This examination serves the purpose of evaluating the impact of the CFRP patch on a metallic details, allowing to validate the attainment of the desired outcomes. Subsequently, this analysis extends to the practical application of the CFRP composite in a real-world scenario, exemplified here by a railway bridge.

Chapter 3

Numerical investigation of strengthening impact in a rectangular plate with central hole

3.1 Introduction

One of the more well-known mechanical and structural problems that affect a variety of industries, including aerospace and automotive parts, is fatigue. Failure of structure damages its constituent parts and endangers people's health. The evaluation of a component's expected service life, which is the sum of the number of loading cycles required to initiate a fatigue crack and the number of cycles required for it to propagate to the critical size, may therefore be significantly complex in the study of such failures in order to arrive at an accurate solution [65].

Local increases in installed stresses result from part geometry irregularities as notches, holes, threads, among others. The stress value can occasionally be calculated using elasticity theory, nevertheless it is typically calculated using computational techniques like the finite element method or experimental mechanics techniques for stress analysis.

Given the time and expense associated with such analyses, a traditional expedient method is to multiply the nominal stresses obtained from the basic expressions of strength of materials for tensile, bending and torsion loading using stress concentration factors (K_t) available in technical tables. These K_t factors, which are based on the presumption that the material is fully homogeneous, isotropic, and elastic, are connected to the geometry of the notches and the method of load application. However, it is important to note that when dealing with more intricate geometries, there may be a lack of available K_t values. This is precisely why K_t is incorporated into the definition of the S-N curve.

The stress concentration factor (K_t) is a dimensionless parameter that quantifies the increase in stress levels at specific locations in structure or component and can be obtained by the following equation, where σ_{max} is the maximum stress and σ_o the nominal stress [66, 67].

$$K_t = \frac{\sigma_{max}}{\sigma_o} \quad (3.1)$$

In the present chapter, it is analysed and discussed an example of rectangular plate with a central hole, under an applied remote uniformly distributed force. The main purpose is to examine the plate's stress behaviour and determine whether the placement of a CFRP patch causes any change.

3.2 Description of the case study

Engineering applications frequently use parts with round holes. The effect of stress concentration can cause cracks to spread in perforated plates specifically subjected to cyclical pressure, jeopardising the structural integrity of the plates. The stress concentration factor (K_t), which is represented in the equation 3.1, is widely used to describe the stress concentration at a geometric discontinuity in a plate [68].

A rectangular plate with a centre hole that is being subjected to tensile force is a common illustration of a stress concentrate, illustrated in the figure 3.1.

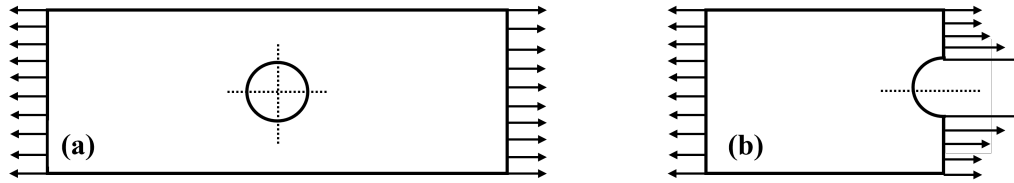


Figure 3.1: Distribution of stress in a plate subjected to tensile load (a) away from the hole and (b) in the section of central hole, adapted from [69]

The tensile stress will be as indicated in figure 3.1(b) through the cross section of the hole. The stress distribution throughout the cut surfaces is essentially uniform until it reaches the area around the hole, where it suddenly increases [69].

The dimensionless stress concentration factor is equal to 3 ($K_t=3$) for this sort of situations, where the diameter is much smaller than the width ($d \ll W$), figure 3.2.

The finite element program *ANSYS* was used to find solutions for numerical models with the previously provided geometric relations, to examine the stress concentration distribution along the edge of a circular hole and plate thickness [70].

In the upcoming sections, the mentioned case study will be analysed in more detail. Due to the symmetry, only 1/4 of the plate was modelled in finite method elements (FEM) and investigated.

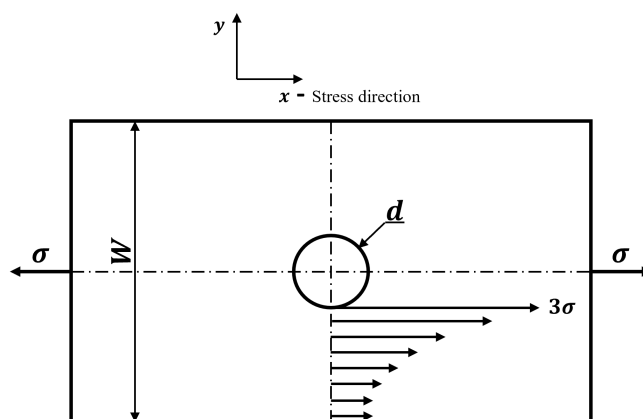


Figure 3.2: Stress distribution in the direction of the applied load, for a plate with a circular hole ($d \ll W$), adapted from [66]

3.3 Geometrical and material definition of the case study

To facilitate the investigation of the case study, an in-depth investigation was undertaken to gather crucial parameters and material properties of the key components, namely steel and CFRP.

At the outset, a thorough exploration of similar instances pertaining to the desired objective was conducted to foster a comprehensive understanding. This comprehensive inquiry included references such as Arteiro et al. [71] and Mohabeddine et al. [10] which provided invaluable insights to develop the model presented in figure 3.3, along with the associated parameters documented in table 3.1. It is important to emphasize that parameter t_{Steel} was chosen taking into account the real case study analysed in chapter 4.

Once the necessary geometrical parameters were obtained, the focus shifted to the process of selecting materials. The plate material was a structural steel, with a modulus of elasticity of 210 GPa and a Poisson coefficient of 0.3. As for the CFRP, an orthotropic material, a comprehensive set of properties was defined, using references such as Yamamoto G. et al. [72] and Shashikala A. et al. [73], presented in the table 3.2. It is important to note that the E_L value for the CFRP patch presented in the table 3.2 serves as the reference value. This value will be modified in one of the subsequent sections for the purpose of conducting a study.

Once all the aforementioned parameters have been acquired, the model is constructed within the ANSYS software. Subsequently, upon implementing the model a distributed load of 100×10^6 N/m² is applied, as visually depicted in figure 3.4.

Regarding the mesh utilized, careful attention was given to employing the SOLID185 element type, purposefully designed for solid modeling within the realm of finite element analysis. This element type boasts eight nodes thoughtfully positioned in the hexahedral arrangement, affording the capacity for interpolation functions, thus enabling accurate stress and strain computations. In order to achieve an optimal level of mesh refinement, an endeavor was made to intricately partition the plate geometry in smaller, well-defined quadrilateral subregions, culminating in the structured mesh configuration showcased in figure 3.5. With regard to the contact between the

CFRP patch and the plate, an ANSYS technique called CONT174-TARG170 was used, which allowed the meshes not to deform and both to have total bounded contact.

Table 3.1: Reference geometric values assigned to the geometric parameters of figure 3.3

Parameters	[m]
a	0.400
b	0.500
t_{Steel}	0.014
t_{CFRP}	0.005
L_3	0.025
L_2	0.150
L_1	0.010

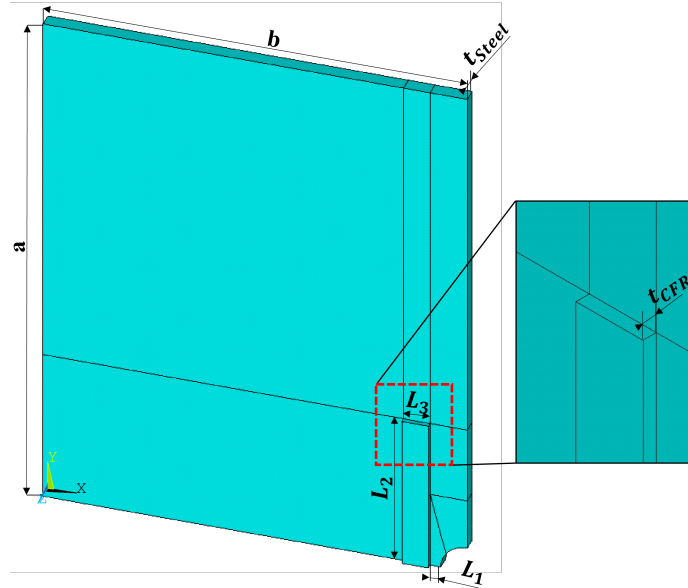


Figure 3.3: Parameters assigned to the model

Table 3.2: Reference elastic properties of CFRP material

Properties	
E_L	640 GPa
E_R	6.62 GPa
E_T	6.62 GPa
G_{LR}	4.88 GPa
G_{LT}	4.88 GPa
G_{RT}	2.48 GPa
ν_{LR}	0.25
ν_{TR}	0.3
ν_{LT}	0.25

Subsequent to the comprehensive analysis of the mesh, careful scrutiny is given to the boundary conditions. Figure 3.6 provides a visual representation from different perspectives, depicting

the associated conditions that predominantly limit movement along the Z-axis. The constraints observed in the X and Y directions arise from the simulation being conducted solely for a quarter plate configuration within the software *ANSYS*.

With a better understanding of the model in question, the next step was to carry out simulations, as shown in subsections 3.5 and 3.4, which are listed in the table 3.3.

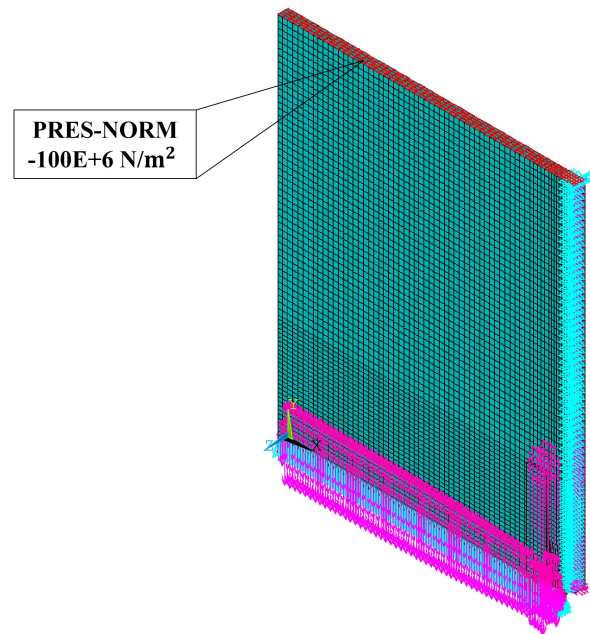


Figure 3.4: Model with the applied load

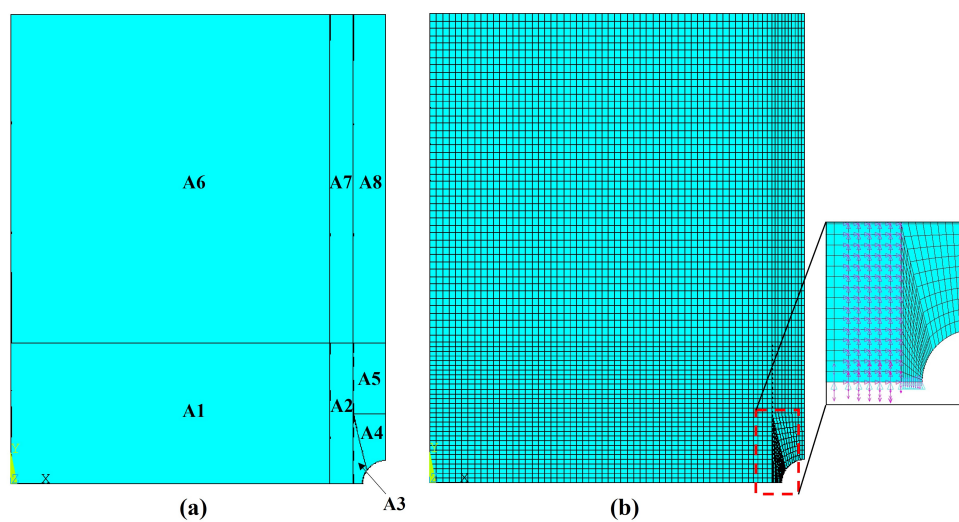


Figure 3.5: *ANSYS* model: (a) Volumes used for the refined mesh and (b) Structured mesh

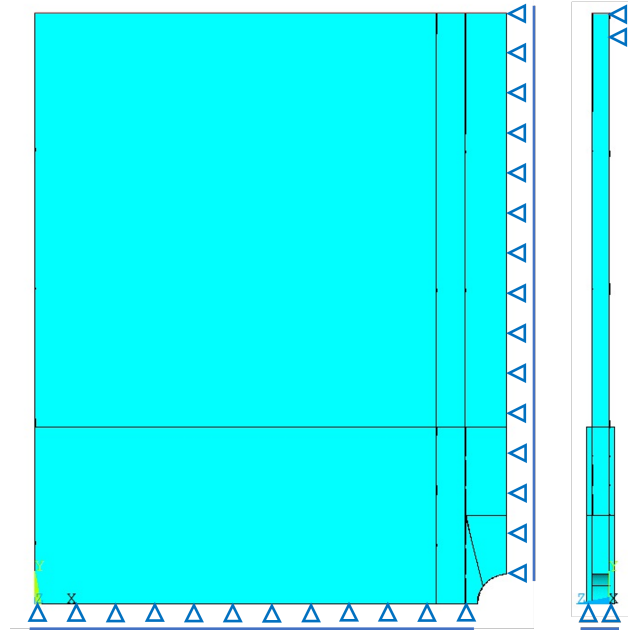


Figure 3.6: Boundary conditions of the model

Table 3.3: Simulation scenarios considered for results analysis

Simulation	Section	
	1 Patch	2 Patches
Effect of CFRP modulus elasticity in K_t	3.4.1	3.5.1
Effect of CFRP thickness in K_t	3.4.2	3.5.2
Effect of CFRP distance to the center hole in K_t	3.4.3	3.5.3
Effect of CFRP length in K_t	3.4.4	3.5.4
Effect of CFRP width in K_t	3.4.5	3.5.5

3.4 Numerical analysis: one CFRP patch

In order to investigate the behavior of the plate under varying parameters, this particular subsection is dedicated to conducting an analysis specifically considering the presence of one CFRP patch positioned at the front of the plate near the hole.

The case study can be approached through two distinct methods: one involves ensuring node continuities, posing a challenge of mesh compatibility, while the other involves the contact between the reinforcement and substrate. Despite their differing approaches, both techniques yield similar outcomes and results.

In this case, the method used involves a full bonded contact between the reinforcement and the substrate, as already mentioned. This approach ensures that a behavior similar to full constituents is achieved, and will serve as the primary approach in the real case study detailed in section 4.

Figure 3.7 illustrates the model of the plate with one CFRP patches applied.

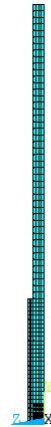


Figure 3.7: Model of the rectangular plate with central hole with 1 patch in ANSYS

3.4.1 Effect of CFRP modulus elasticity in K_t

Initially, the mechanical properties of the case study were subjected to analysis, specifically focusing on the variation of the longitudinal modulus of elasticity ranging from 100 GPa to 640 GPa. For each modulus of elasticity of the CFRP, the stress concentration factor was calculated. This wide range of modulus of elasticity values was employed to examine and compare the stress concentration factor variations when the modulus of elasticity is lower, equal, or higher than that of the steel.

Upon gathering the data from this analysis, figure 3.8 was obtained, illustrating the variation of K_t for values greater, equal, and less than the modulus of elasticity of steel. Three points are indicated on the graph: (a) 100 GPa, representing the lowest value; (b) 220 GPa, an approximate value of the modulus of elasticity of steel; and (c) 640 GPa, signifying the highest value.

Upon obtaining and thoroughly analyzing the results, it was surprising to observe that they deviated from the expected outcome. This was unexpected, as one would anticipate higher values of K_t for lower values of E . However, in this case, an increase in E_{CFRP} leads to a corresponding increase in K_t , which contradicts the initial expectation. It's worth highlighting that the graph referenced as 3.8 displays K_t values exceeding 3, and this phenomenon can be attributed to the eccentricity effect. This effect arises from the fact that the stress distribution in the plate is uniform when the CFRP patch is not applied. However, the introduction of the CFRP patch in one plate side alters the load's eccentricity, leading to results diverging from initial expectations.

In this specific scenario, the surprisingly result of the increased E_{CFRP} is the amplification of eccentricity, which, in turn, leads to an escalation in local stress, due to plate bending, and as a consequence, an increase in K_t occurs.

Finally, to gain a more comprehensive understanding of the deformations, a contour plot extracted from the ANSYS software was acquired, as shown in Figure 3.9. This chart facilitated the examination of the maximum stress values for each of the three selected points.

To assess the bending, figure 3.7 displays the plate with the applied CFRP, while figure 3.10 portrays the same scenario, allowing for the analysis of bending resulting from the CFRP patch.

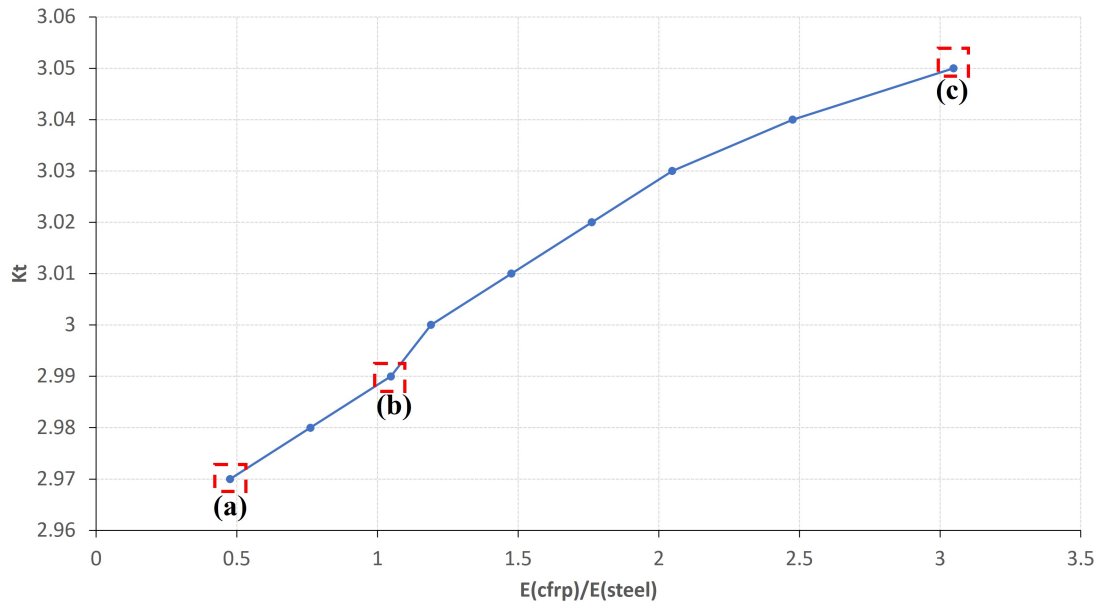


Figure 3.8: Effect of Young Modulus of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $E_L=100$ GPa, (b) $E_L=220$ GPa and (c) $E_L=640$ GPa

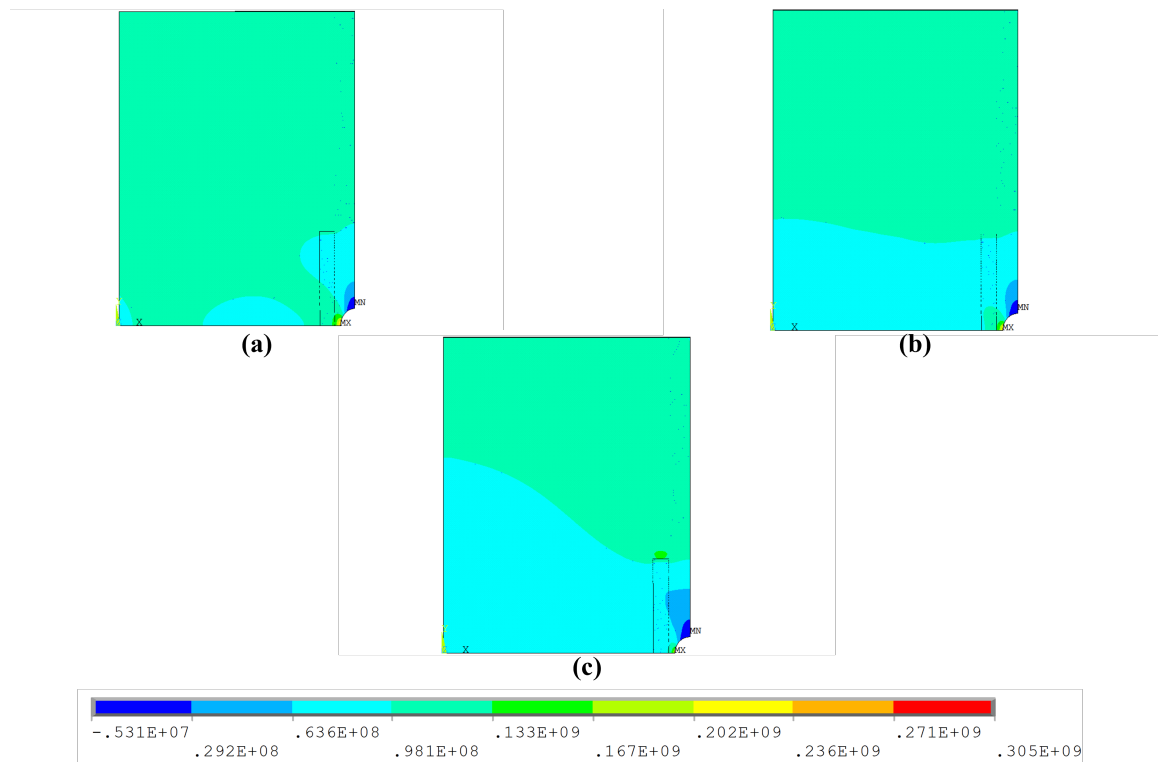


Figure 3.9: Variation of the stress according to the modulus of elasticity for one patch: (a) $E_L=100$ GPa, (b) $E_L=220$ GPa and (c) $E_L=640$ GPa

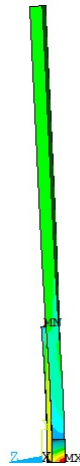


Figure 3.10: Model of the rectangular plate with central hole with 1 patch in *ANSYS* with bending

3.4.2 Effect of CFRP thickness in K_t

Following the examination of the mechanical properties, specifically exploring the relationship between the modulus of elasticity and the stress concentration factor, a subsequent phase of the study entails a geometric analysis.

The present study aims to examine the response of the stress concentration factor K_t as the thickness of the CFRP varies.

The primary objective of this analysis is to examine how K_t varies with changes in the CFRP thickness. The results obtained for thicknesses smaller, equal, and larger than that of the steel are illustrated in figure 3.11. Upon an initial examination of the graph, it becomes apparent that K_t values exceeding 3 result from the eccentricity effect, which arises due to the presence of only sided CFRP patch. To validate the obtained results, contour plots were generated, figure 3.12, displaying the maximum stress values for the three points indicated in figure 3.11: (a) 0.005 m, (b) 0.013888 m, and (c) 0.025 m.

It becomes evident that the observed results deviate from anticipated outcome, primarily due to the resemblance of the curve to a downward-facing parabola. These findings present a surprising aspect, surpassing the level of unexpectedness experienced in the previous example. As previously noted, there exist values of K_t where the magnitude exceeds 3. This phenomenon can be attributed to the influence of eccentricity.

Through the utilization of *ANSYS* software, it was ascertained that with an increase in the CFRP thickness, the plate became more susceptible to bending, at an initial moment. This phenomenon can be attributed to the fact that the increase in CFRP thickness leads to a shift in the center of gravity, as only one CFRP patch is utilized. Consequently, this change in the center of gravity results in an increased eccentricity and bending, subsequently leading to an increase in the moment. This observation may elucidate the discrepancy observed in the curve when compared to the initial expectations.

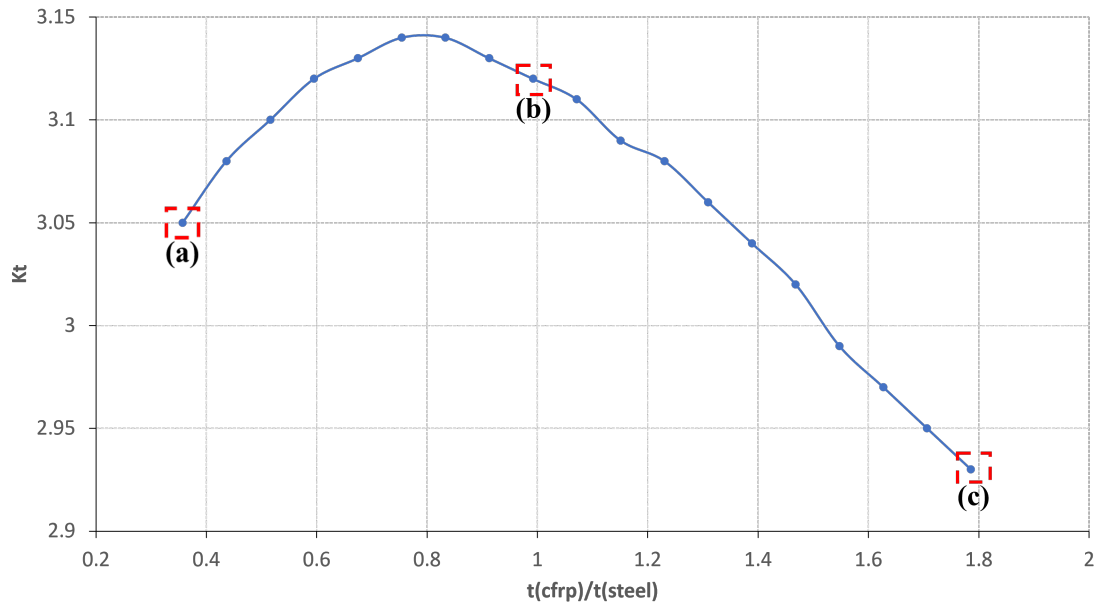


Figure 3.11: Effect of thickness of CFRP patch in the elastic stress concentration factor in the steel plate : (a) $t_{CFRP}=0.005$ m, (b) $t_{CFRP}=0.013888$ m and (c) $t_{CFRP}=0.025$ m

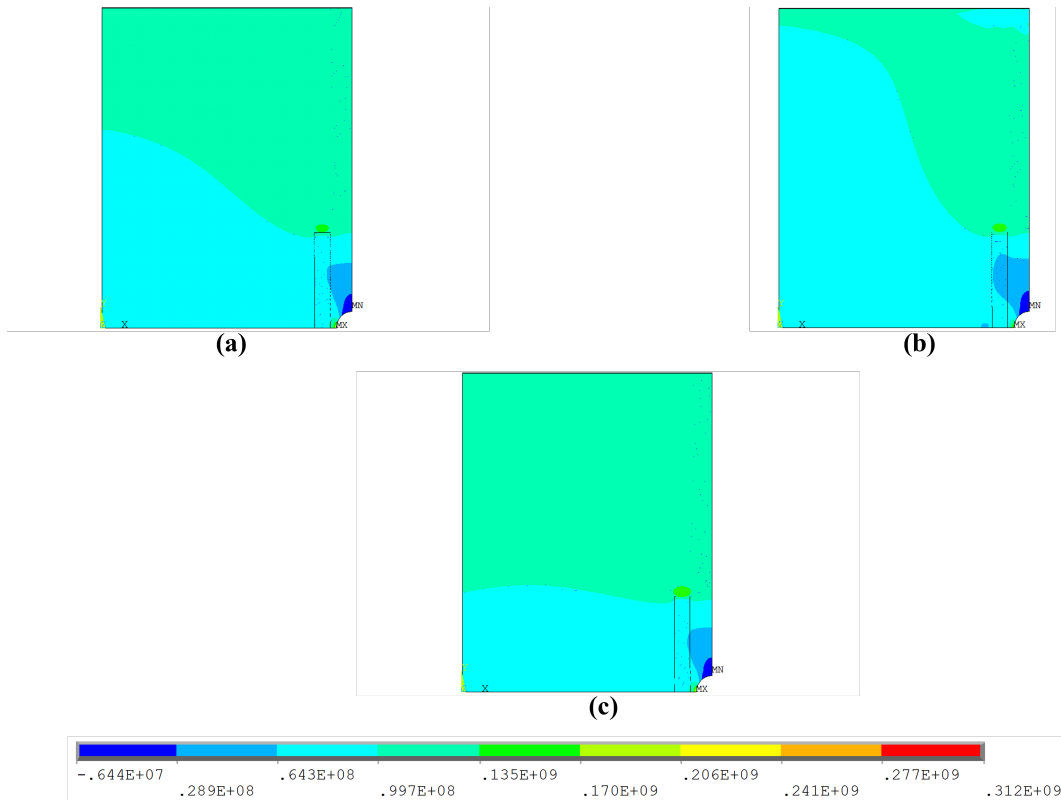


Figure 3.12: Variation of the stress according to the variation of the CFRP thickness: (a) $t_{CFRP}=0.005$ m, (b) $t_{CFRP}=0.013888$ m and (c) $t_{CFRP}=0.025$ m

However, starting from $x=0.8$ onwards, it becomes evident that with an increase in CFRP thickness, the value of K_t decreases as intended. This phenomenon arises because, initially, the increase in CFRP thickness doesn't have a substantial effect, resulting in bending. Nonetheless, after $x=0.8$, the impact of the increased CFRP thickness becomes noticeable, counteracting the bending induced by the plate, ultimately resulting in a reduction in K_t .

3.4.3 Effect of CFRP distance to the center hole in K_t

To further the geometric analysis, a decision was made to investigate the behavior of the parameter K_t in relation to the distance of the CFRP patch from the hole.

After a careful examination of the results depicted in figure 3.13, it becomes evident that, once again, the observed outcomes deviate from the expected ones.

Nonetheless, a significant disparity becomes apparent, as the results not only diverge from the anticipated but also reveal an inverse correlation. Specifically, in the present scenario, augmenting the distance between the CFRP patch and the hole, results in a proportional decrease in the K_t value. Consequently, this brings about an increase in fatigue resistance and renders the region more susceptible to this phenomenon.

It's worth noting that in this scenario, there is no shift in the center of gravity, as only one of the eccentricities varies. Nevertheless, since it is the least significant one, its impact is not noteworthy when considering the effects of eccentricity.

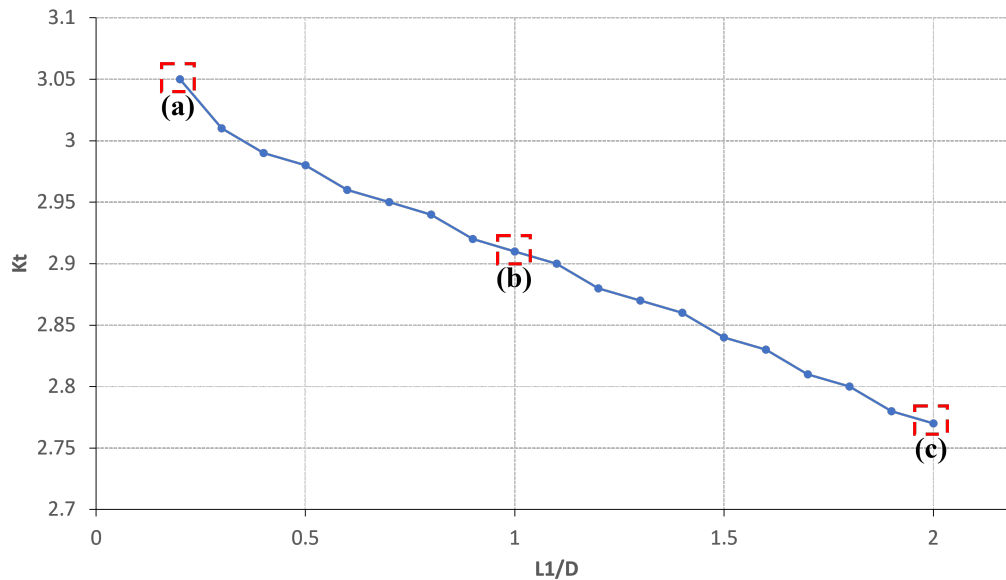


Figure 3.13: Effect of distance to the center hole of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_1=0.010$ m, (b) $L_1=0.050$ m, and (c) $L_1=0.100$ m

To obtain a more precise analysis of the results, contour plots representing the stresses at three points: (a) $L_1=0.010$ m, (b) $L_1=0.050$ m, and (c) $L_1=0.100$ m were extracted from the ANSYS program. This is represented in figure 3.14 where it is possible to observe the respective maximum

stress, confirming the previous conclusion that the greater the distance of the CFRP patch to the hole, the lower this stress becomes. The observed outcome can be attributed to the proximity of the CFRP to the load, which reduces the out-of-plane bending moment. This reduction results in diminished plate stress at the location of maximum tension, thus causing a variation in eccentricity.

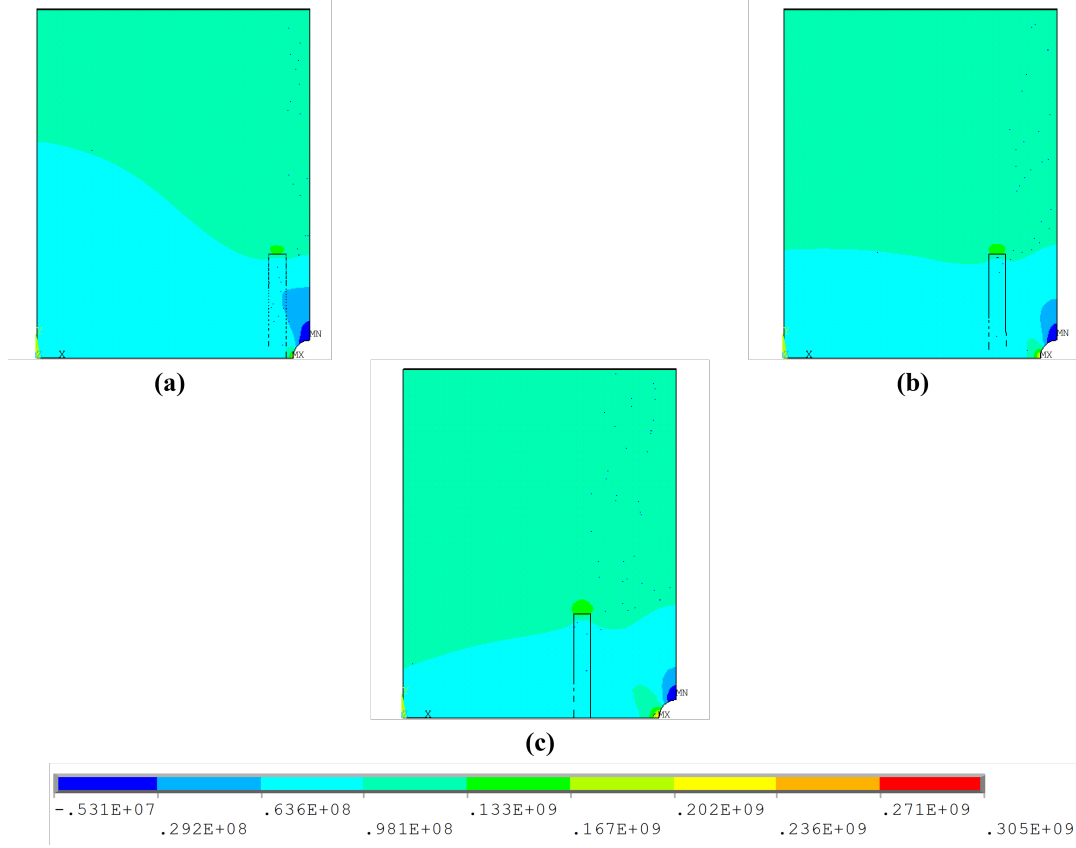


Figure 3.14: Variation of the stress according to the distance of the CFRP to the center hole: (a) $L_1=0.010$ m, (b) $L_1=0.050$ m, and (c) $L_1=0.100$ m

3.4.4 Effect of CFRP length in K_t

Continuing with the geometric analysis, the focus now shifts to understanding the behavior of K_t in relation to variations in the length of the CFRP patch.

Exploring different CFRP lengths, including values smaller, larger, and equal to the hole diameter, three key points are specifically highlighted: (a) $L_2=0.0350$ m, the lowest value; (b) $L_2=0.050$ m, which is equal to the diameter; and (c) $L_2=0.150$ m, representing the reference value.

The results obtained were gathered and presented in figure 3.15, showcasing the relationship between the ratio $\frac{L_2}{D}$ and K_t . Upon observation, it is evident that increasing the length of the CFRP patch leads to a decrease in K_t , meaning that the maximum stress decreases. This reduction in K_t subsequently enhances the fatigue strength of the structure.

To gain a better understanding of the case under analysis, the ANSYS program was utilized to obtain contour plots corresponding to the three mentioned points, as shown in figure 3.16.

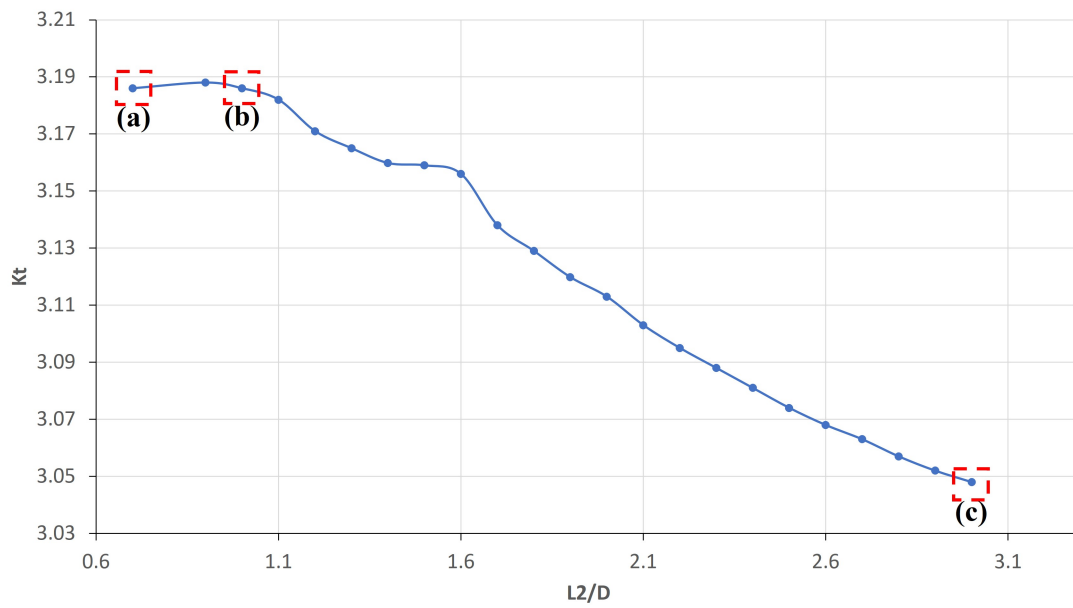


Figure 3.15: Effect of the length of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_2=0.035$ m, (b) $L_2=0.050$ m and (c) $L_2=0.150$ m

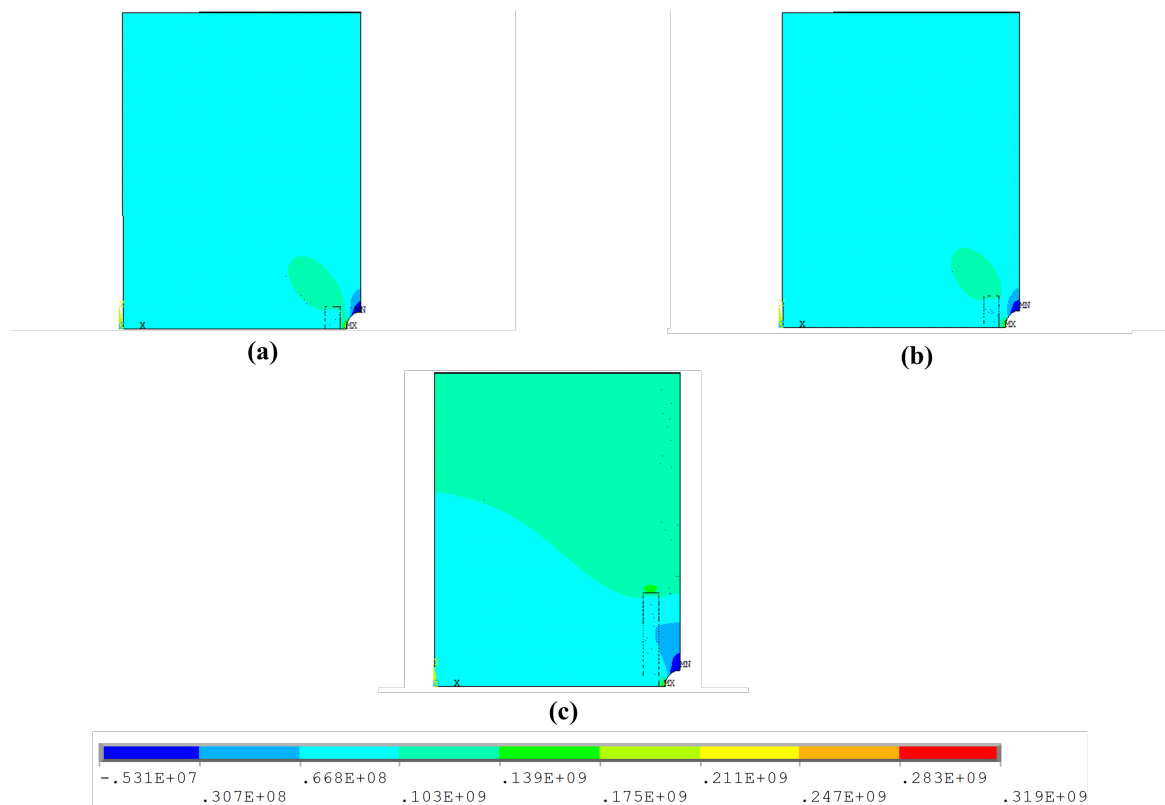


Figure 3.16: Variation of the stress according to the CFRP length: (a) $L_2=0.035$ m, (b) $L_2=0.050$ m and (c) $L_2=0.150$ m

Figure 3.16 presents the variation of the CFRP patch length, displaying the color scale according to the stresses, including the maximum stress values. In contrast to the previous cases, the current scenario yields results that closely align with the expected outcomes.

Additionally, it is worth noting that figure 3.15 exhibits certain fluctuations as the length of the CFRP patch increases. These variations can be attributed to slight fluctuations in the maximum stress during the simulation process.

3.4.5 Effect of CFRP width in K_t

The primary objective of this section is to analyse the behavior of K_t as the width of the CFRP patch is varied.

The width of the CFRP was altered to values smaller, equal, and larger than the diameter of the plate, with three key points highlighted: (a) 0.010 m, representing the lowest value; (b) 0.050 m, representing the diameter value; and (c) 0.100 m, representing the highest value.

Subsequently, the results were gathered and presented in figure 3.17. To gain a more precise understanding, the contour plots corresponding to the three marked points were also obtained, illustrating the stress scales along with the maximum stress displayed in figure 3.18.

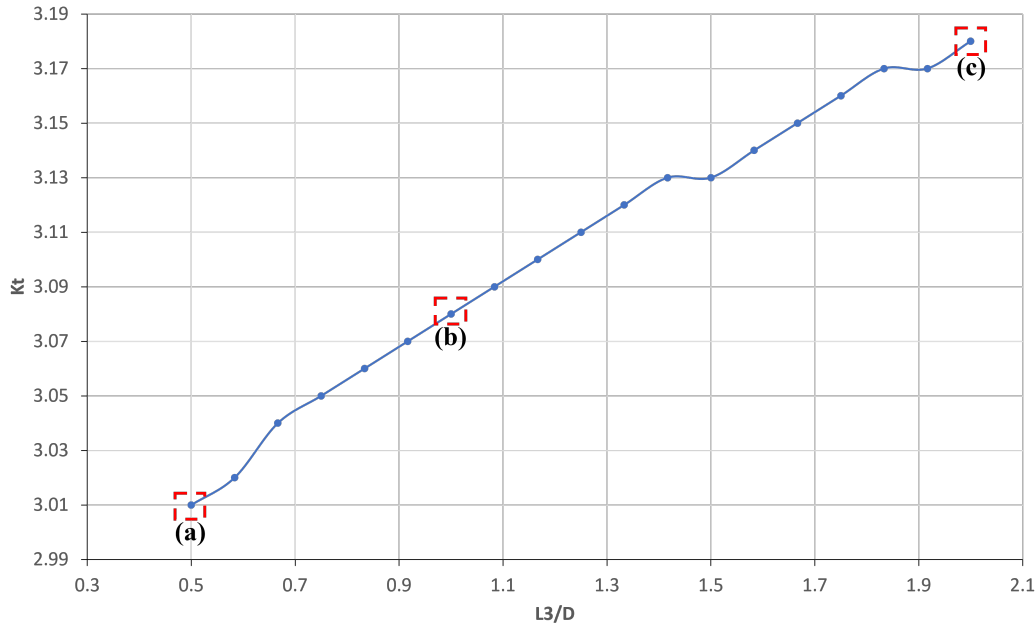


Figure 3.17: Effect of the width of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_3=0.010$ m, (b) $L_3=0.050$ m and (c) $L_3=0.100$ m

Upon thorough examination of the provided images, 3.17 and 3.18, it becomes evident that an expansion in the width of the CFRP patch results in an increase in K_t . This, in turn, is detrimental to fatigue resistance due to the widening of the patch, which subsequently increases the mass and load eccentricity.

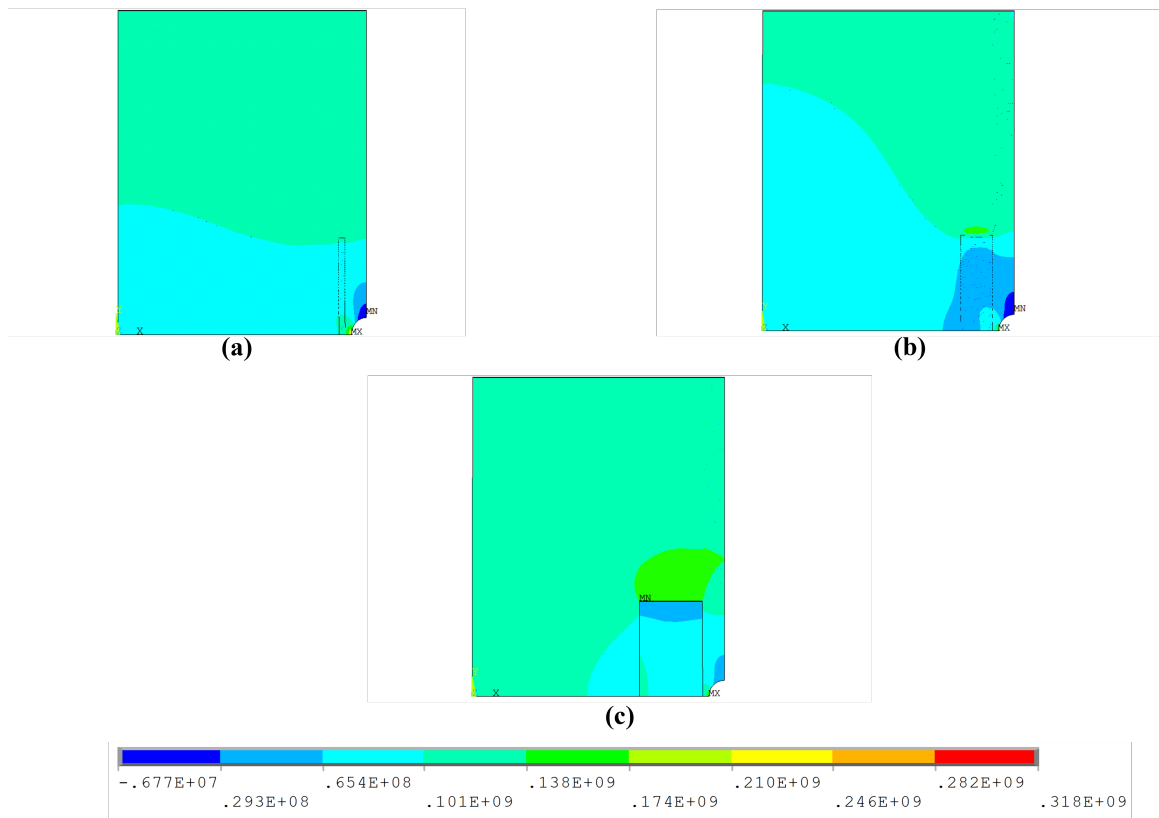


Figure 3.18: Variation of the stress according to the CFRP width: (a) $L_3=0.010$ m, (b) $L_3=0.050$ m and (c) $L_3=0.100$ m

These outcomes run counter to expectations, as one would anticipate that enlarging the width of the CFRP patch would result in a reduction of its stress concentration factor, K_t . This is owing to the assumption that the critical detail zone would be more effectively reinforced.

3.4.6 Concluding remarks and critical analysis

The primary focus of this section 3.4 is to analyse the behavior of the parameter K_t in relation to changes in mechanical properties and geometric parameters, for one CFRP patch.

The significant variation in the obtained results can be attributed to the use of a one-sided CFRP patch, which unavoidably causes bending. As a result, changes in the parameters cause a shift in the center of gravity and give rise to the eccentricity effect. To be more specific, the center of gravity moves farther away, leading to increased bending loading effects.

Figure 3.7 portrays the *ANSYS* model of a rectangular plate with a central hole, featuring solitary CFRP patch applied to it.

Upon acquiring the figure 3.7, it becomes possible to extract the relevant data, specifically the Y-component of stress, as illustrated in figure 3.10. Subsequently, it is possible verifying the out-of-plane bending originated by the shift of the center of gravity due to the added CFRP patch.

During the simulation using *ANSYS* to observe the actual results, an interesting discovery was made. Contrary to the initial predictions, the observed outcomes were opposite. The unexpected difference can be explained by the bending forces exerted on the plate and the presence of eccentricities, both of which lead to the plate's appearance as depicted in Figure 3.10. This raises concerns about the effectiveness of the CFRP patch in certain details, under specific load.

Therefore, a decision was made to conduct a new analysis, this time with the application of two sided CFRP patches. The goal was to eliminate the out-of-plane eccentricity effect, thereby bringing the results closer to what would occur in a real-world scenario.

3.5 Numerical analysis: two CFRP patches

Subsequent to applying a CFRP patch to a steel plate featuring a central hole, and realizing that the outcomes did not align with expectations, a decision was made to address the situation through a fresh analysis. In this new approach, two CFRP patches would be applied, positioned at the front and rear of the plate.

Consistently, the two analysis methods were upheld: one involving the maintenance of node continuity, thereby posing a challenge of mesh compatibility. The other method entails contact between the reinforcement and the substrate. Just as before, the latter approach involving contact is favored. This choice is grounded in its alignment with the methodology slated for utilization in the real case study expounded in Section 4.

In a manner consistent with previous efforts, identical simulations were conducted for the following ratios variation: $\frac{L_1}{D}$, $\frac{L_2}{D}$, $\frac{L_3}{D}$, $\frac{t_{CFRP}}{t_{Steel}}$ and $\frac{E_{CFRP}}{E_{Steel}}$ and their effects in the investigation.

Figure 3.19 illustrates the model of the plate with both CFRP patches applied.

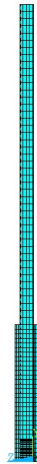


Figure 3.19: Model of the rectangular plate with central hole with 2 patch in *ANSYS*

3.5.1 Effect of CFRP modulus elasticity in K_t

The analysis commenced with an examination of the mechanical properties specifically the modulus of elasticity. As previously stated, the modulus of elasticity of CFRP was systematically varied to investigate the behavior of K_t .

According to the results depicted in figure 3.20, the findings indicate a notable trend as the ratio $\frac{E(CFRP)}{E(steel)}$ increases, indicating a higher modulus of elasticity for CFRP in relation to steel, the corresponding stress concentration factor consistently decreases, aligning with expectations and theoretical predictions.

With emphasis, the salient points unfurl, unveiling the manifold variations of the modulus of elasticity. The values include (a) $E_L=100$ GPa, representing the lowest value; (b) $E_L=220$ GPa, which bears the closest resemblance to the Young's modulus of steel; and (c) $E_L=640$ GPa, signifying the highest value.

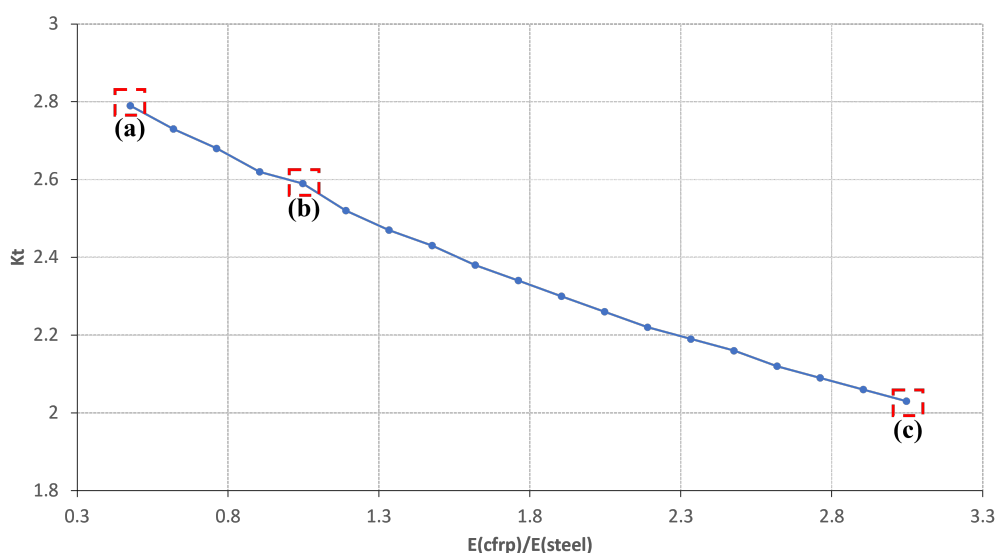


Figure 3.20: Effect of Young Modulus of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $E_L=100$ GPa, (b) $E_L=220$ GPa and (c) $E_L=640$ GPa

Indubitably, the examination of figure 3.20 reveals an increase in the modulus of elasticity of CFRP, when juxtaposed with steel plate, yields highly favorable ramifications in terms of fatigue performance. This conclusion emanates from the consistent diminishment of the stress concentration factor as the modulus of elasticity of CFRP steadily ascends, thus affirming its superior fatigue-resistant properties in comparison to steel.

To corroborate the conclusions, a comprehensive examination of the stress fields, figure 3.21, was conducted for the specified modulus of elasticity values. By using contour plots, the fluctuation of stress levels with the ascending modulus of elasticity was discerned, thereby solidifying and validating the previously established assertions.

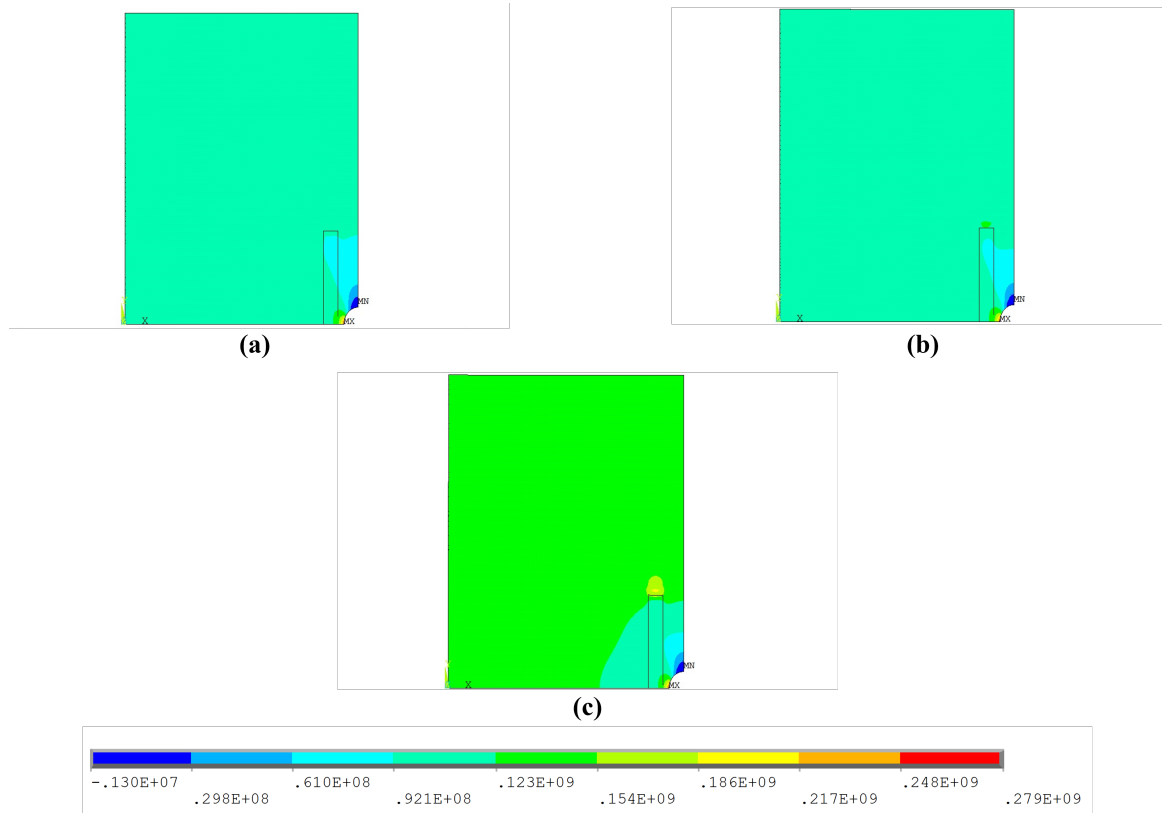


Figure 3.21: Variation of the stress according to the modulus of elasticity: (a) $E_L=100$ GPa, (b) $E_L=220$ GPa and (c) $E_L=640$ GPa

3.5.2 Effect of CFRP thickness in K_t

To further delve into the geometric analysis, a decision was made to explore the behavior of the K_t parameter concerning variations in the thickness of the CFRP patch positioned adjacent to the hole.

Figure 3.22 illustrates the present study analysis, specifically focusing on the relationship between the ratio of $\frac{t(CFRP)}{t(steel)}$ and the stress concentration factor (K_t). The CFRP thickness was varied across values smaller, equal, and larger than the thickness of the steel.

Based on the analysis conducted, it can be deduced that the impact of varying the CFRP thickness is predominantly observed during the initial stages, specifically for values smaller or equal to the thickness of the steel material, point (b) in figure 3.22. Furthermore, it has been observed that once the CFRP thickness approaches that of the steel thickness, the stress concentration factor (K_t) stabilizes and remains relatively constant.

In order to substantiate the previously mentioned claims, software *ANSYS* was used to generate contour plots encompassing various data points. Careful consideration led us to focus on merely three critical points, namely: (a) $t_{CFRP}=0.005$ m, representing the reference value for CFRP thickness; (b) $t_{CFRP}=0.013888$ m, which approximates $t_{CFRP}=0.014$ m and equals the thickness of the steel, mirroring the actual thickness value utilized in the real-life scenario presented in chapter 4; and (c) $t_{CFRP}=0.025$ m, a larger value chosen to facilitate a distinct comparative assessment.

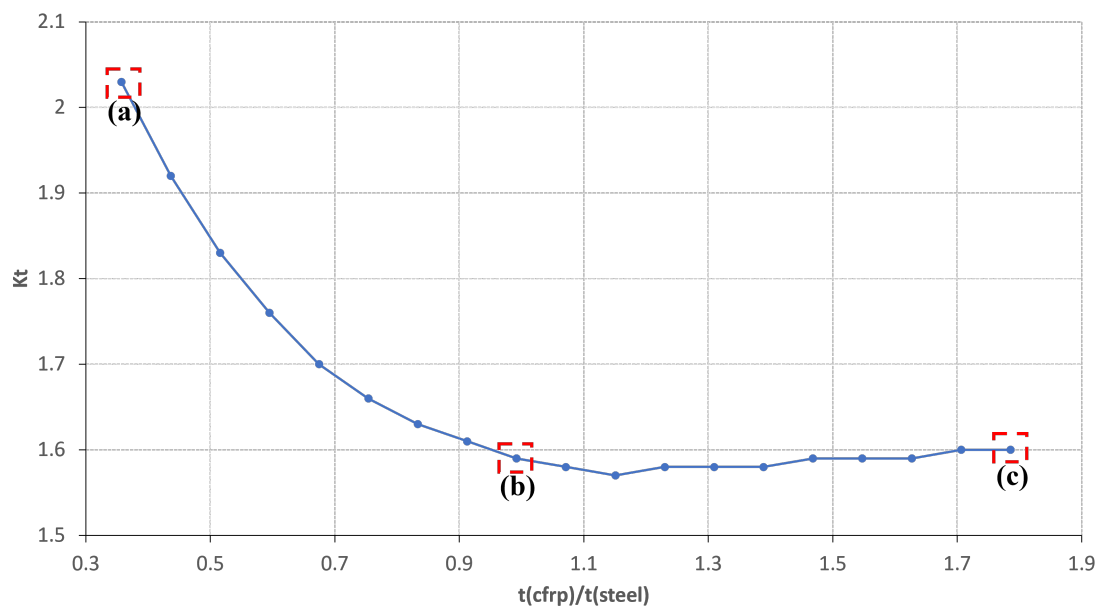


Figure 3.22: Effect of thickness of CFRP patch in the elastic stress concentration factor in the steel plate : (a) $t_{CFRP}=0.005$ m, (b) $t_{CFRP}=0.013888$ m and (c) $t_{CFRP}=0.025$ m

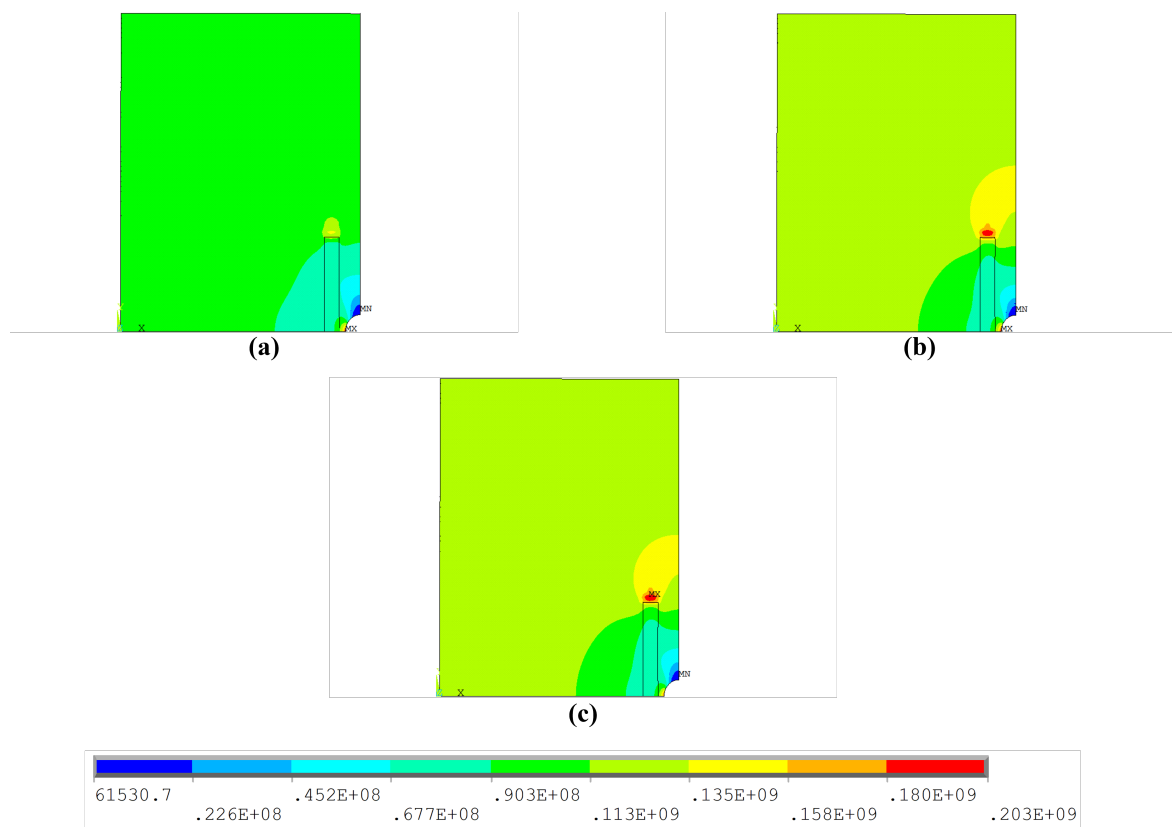


Figure 3.23: Variation of the stress according to the variation of the CFRP thickness: (a) $t_{CFRP}=0.005$ m, (b) $t_{CFRP}=0.013888$ m and (c) $t_{CFRP}=0.025$ m

Upon scrutinizing figure 3.23, one stumbles upon the visual representation of the three aforementioned points, thereby affirming the anticipated results. Notably, with an increase in CFRP thickness, a discernible reduction in maximum stress ensues, consequently yielding a decrement in the value of K_t . Thus, it becomes evident that augmenting the CFRP thickness yields a increase in the resistance against fatigue. However, it is worth noting that beyond point (b), the values of K_t stabilize at approximately constant levels.

3.5.3 Effect of CFRP distance to the center hole in K_t

In this specific scenario, it was conducted a variation in the distance between the CFRP patches and the hole to investigate the stress concentration factor's behavior as the distance is incrementally increased.

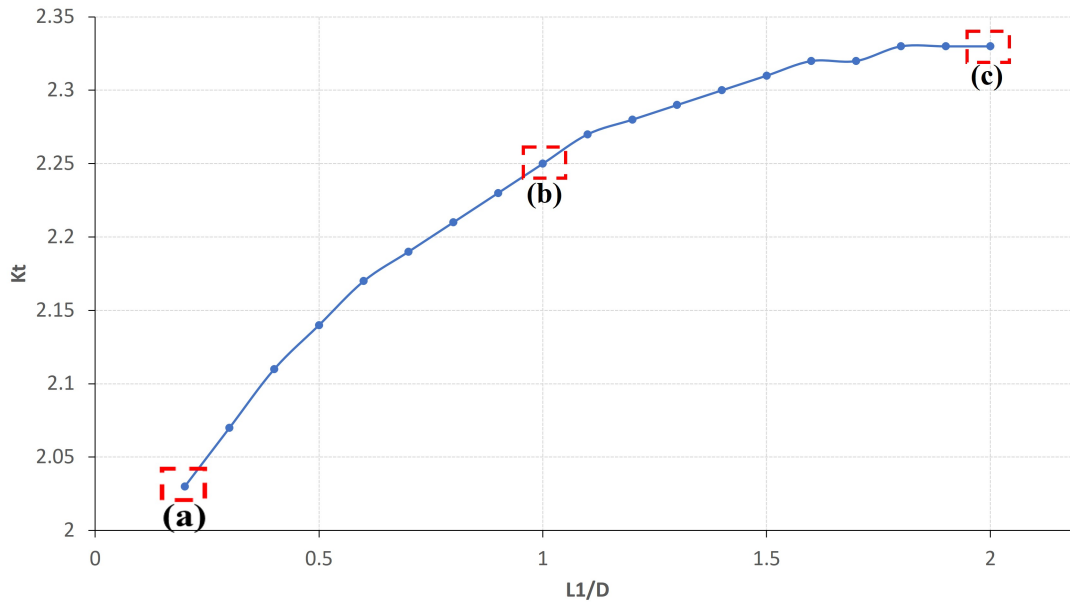


Figure 3.24: Effect of distance to the center hole of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_1=0.010$ m, (b) $L_1=0.050$ m, and (c) $L_1=0.100$ m

Figure 3.24 depicts the results of the aforementioned analysis. During this investigation, it was manipulated the distance using values that were lower, equal, and higher than the hole's diameter. The figure presents an analysis that showcases the progression of the $\frac{L_1}{D}$ ratio alongside the stress concentration factor (K_t).

Upon analysing the figure, it becomes apparent that an increased distance from the CFRP patch results in an elevated K_t value. This signifies a greater likelihood of fatigue occurrence, thereby impeding the extension of the plate's useful lifespan. Therefore, it can be inferred that in order to achieve superior outcomes, it is advisable to position the CFRP patch in immediate proximity to the aperture.

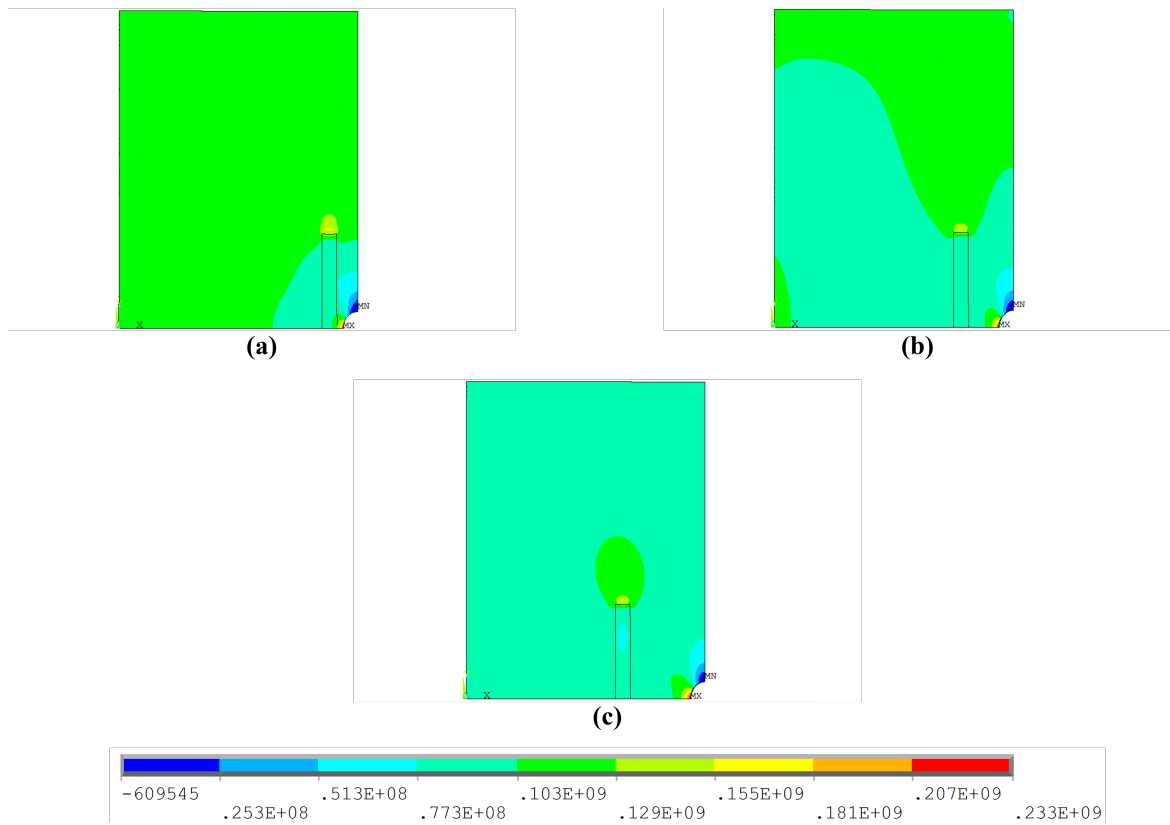


Figure 3.25: Variation of the stress according to the distance of the CFRP to the center hole: (a) $L_1=0.010$ m, (b) $L_1=0.050$ m, and (c) $L_1=0.100$ m

To validate the findings, the precedent analysis was conducted employing the *ANSYS* software, which enabled the extraction of visual representations comprising graphs and color-coded indicators. These insightful images facilitated the identification of stress points and the determinations of maximum stress values.

Upon careful examination of figure 3.25, it is possible to reinforce the previous conclusions: as the distance of the CFRP patch from the center hole increases, maximum stress also intensifies, thereby resulting in an increase of K_t .

3.5.4 Effect of CFRP length in K_t

In the current investigation, an analysis is conducted to examine the behavior of stress concentrations with respect to the varying length of CFRP.

Figure 3.26 displays the outcomes obtained, wherein the length is systematically adjusted to encompass values exceeding, equaling, or falling short of the hole diameter. The highest value corresponds to the reference value in this context.

Upon careful examination of the acquired results, it was determined that the decrease in CFRP length correlates with a corresponding exponential reduction in the K_t . Ultimately, as the $\frac{L_2}{D}$ ratio approaches 2, the K_t value stabilizes and demonstrates a higher degree of constancy.

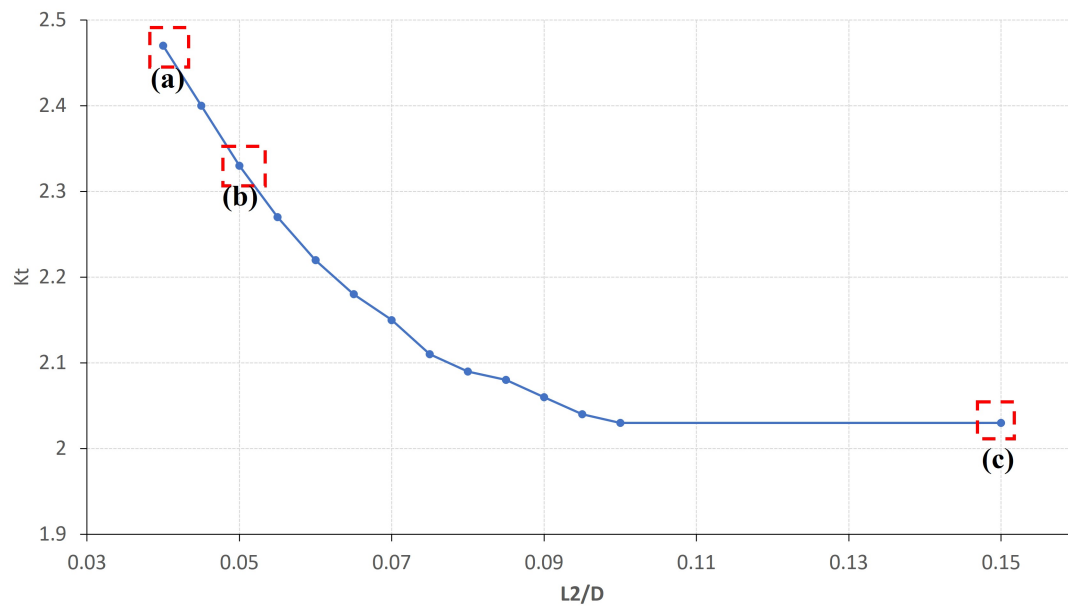


Figure 3.26: Effect of the length of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_2=0.035$ m, (b) $L_2=0.050$ m and (c) $L_2=0.150$ m

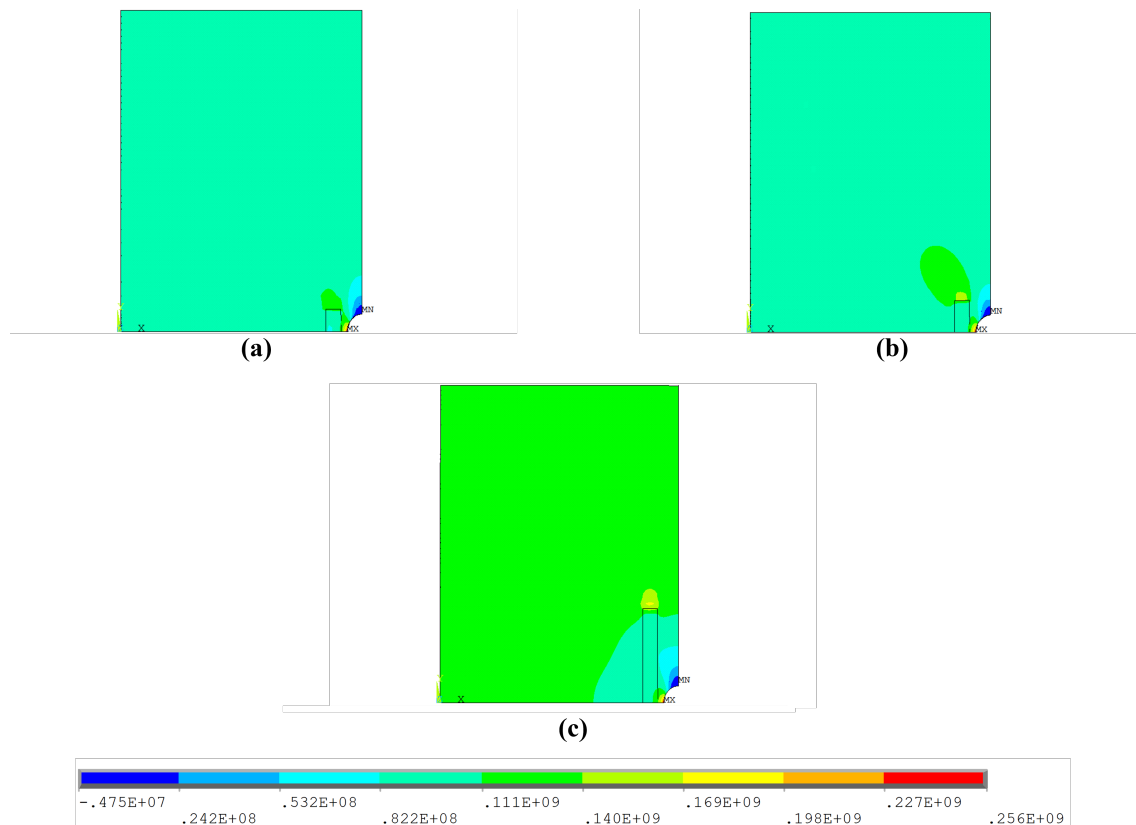


Figure 3.27: Variation of the stress according to the CFRP length: (a) $L_2=0.035$ m, (b) $L_2=0.050$ m and (c) $L_2=0.150$ m

Based on the prior mentioned observations, it becomes apparent that the reduction in CFRP length inadvertently elevates the likelihood of fatigue incidents, thereby contradicting the intended objective.

In pursuit of a heightened level of precision in our analysis, a deliberate selection was made to focus on three distinct points along the plate, investigating the fluctuations in stresses through the use of color-coded graphs. Accordingly, the chosen points, denoted as (a) 0.150 m, (b) 0.050 m, and (c) 0.035 m, have been visually represented in figure 3.26, while the corresponding contour plots illustrating stress distributions have been presented in Figure 3.27.

After conducting a comprehensive analysis of figure 3.27, a striking correlation becomes apparent, affirming the conclusion drawn from the examination of Figure 3.26. Specifically, as the length of the CFRP patch diminishes, there is a discernible upsurge in both the maximum stress and the corresponding K_t value.

3.5.5 Effect of CFRP width in K_t

The goal of the present analysis is to explore alterations in the K_t while methodically varying the width of the CFRP patch. This inquiry encompasses width values that are both smaller and larger than the diameter of interest, in addition to values that are equal to it.

Figure 3.28 illustrates the correlation between K_t and the $\frac{L_3}{D}$ ratio. Upon a thorough examination of the figure, it becomes evident that as the $\frac{L_3}{D}$ ratio, signifying an enlargement of the CFRP patches width, increases, there is a corresponding decrease in K_t and, consequently, in the local stress.

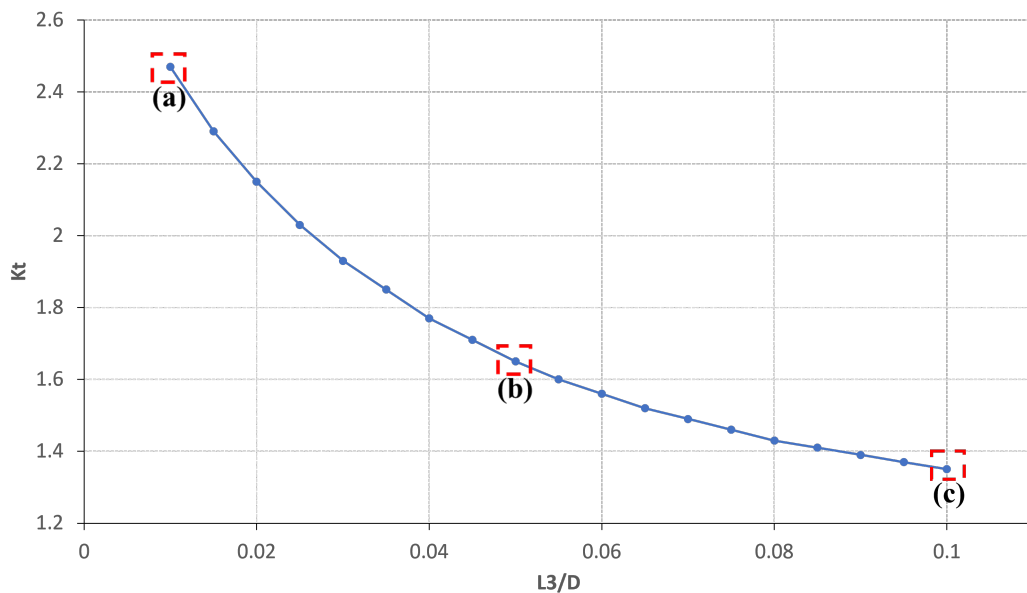


Figure 3.28: Effect of the width of CFRP patch in the elastic stress concentration factor in the steel plate: (a) $L_3=0.010$ m, (b) $L_3=0.050$ m and (c) $L_3=0.100$ m

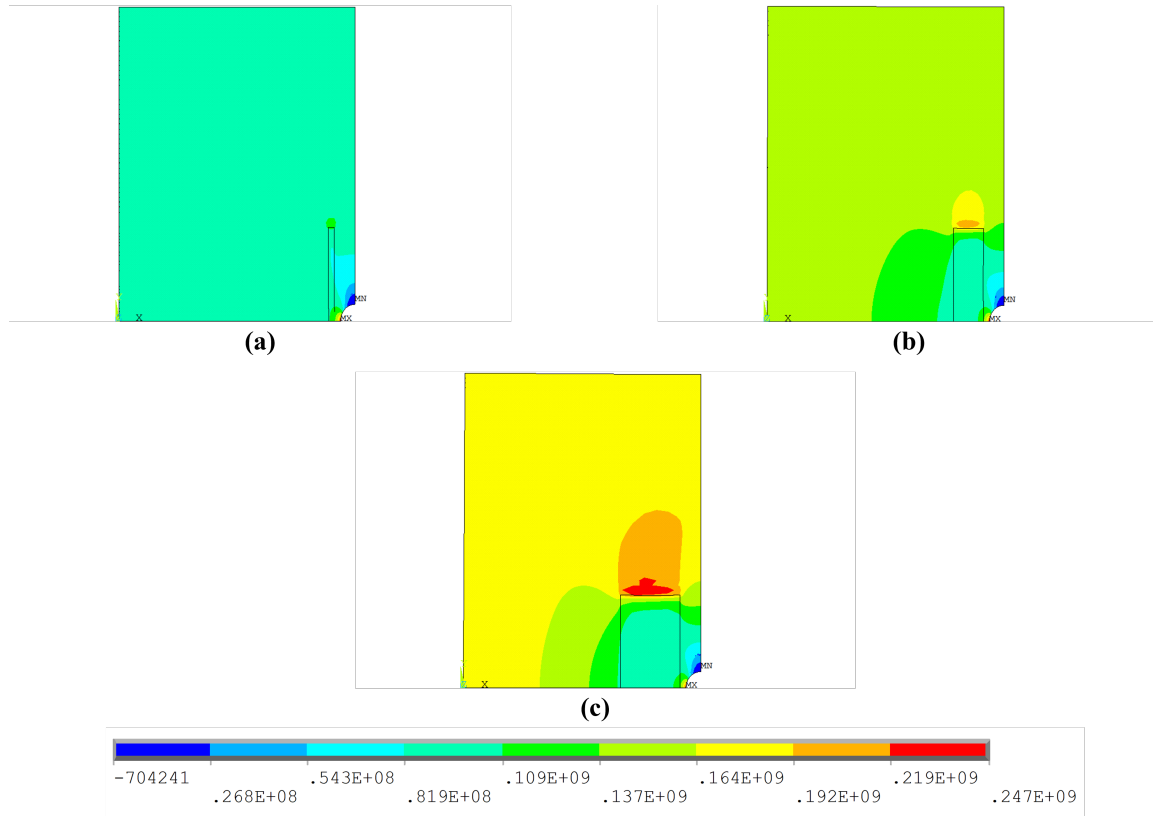


Figure 3.29: Variation of the stress according to the CFRP width: (a) $L_3=0.010$ m, (b) $L_3=0.050$ m and (c) $L_3=0.100$ m

Therefore, it can be deduced that expanding the width of the CFRP patch diminishes fatigue damage under cyclic loading conditions, thereby conferring benefits for its intended purpose — namely, enhancing the durability of the plate.

In the pursuit of a more comprehensive analysis, three strategic points were carefully selected from figure 3.28. These points, namely (a) 0.010 m; (b) 0.050 m, equivalent to the diameter; and (c) 0.10 m, were deliberately chosen to ensure a well-rounded investigation.

Subsequently, the distinctive contour plots for each of these points were generated, unveiling invaluable insights into their respective stress distributions.

Therefore, this study reaffirms the initial conclusion that an increase in the width of the CFRP patch leads to a reduction in the maximum tension, consequently resulting in a decrease in the corresponding K_t value.

3.5.6 Concluding remarks and critical analysis

The purpose of conducting the case study analysis in the subchapter 3.5, was to explore and investigate the K_t in a rectangular plate with central hole and two CFRP patches, specifically focusing on how it responds to variations in mechanical and geometric parameters. Upon acquiring and scrutinizing each of the individual results, it was observed that they were consistent with the anticipated expectations. Specifically, after conducting all the intended analyses, it was revealed

that only the analysis focusing on the distance from the CFRP patch to the hole demonstrated and increase in the K_t results as the $\frac{L_1}{D}$ ratio increased.

Among all the conducted analyses, it was determined that the CFRP width variation produced the lowest value of K_t , approximately measuring 1.35.

The two symmetrical CFRP patches are applied to the plate, as depicted in figure 3.19, resulting in a more uniform distribution of the load across the entire structure. The inherent symmetry of this arrangement further aids in the equilibrium of forces and mitigates stress concentrations at edges of the hole, thereby yielding superior results compared to those attained in subsection 3.4.

In reference to the analysis conducted in the preceding chapter, 3.4, and drawing a comparison with the outcomes derived in this chapter, the initial anticipation was for results similar to those obtained in this analysis, albeit with elevated K_t values for the chapter 3.4. The objective behind the inclusion of the CFRP patch was to counteract the impacts of fatigue, consequently yielding reduced K_t values compared to those anticipated in the absence of one of the two CFRP patches.

3.6 Concluding remarks

The present chapter aims to conduct a study on a simplified example to analyse the behavior of CFRP as specific parameters were varied. The purpose of this study is to verify the feasibility of progressing to the next stage, which involves analysing the behavior of a CFRP strip in a real-world scenario, specifically, the Várzeas Bridge.

Sections 3.4 and 3.5 presented the results of the analysis of the behavior of one CFRP patch and two CFRP patches, respectively. After obtaining and analysing the respective results, a comparison was made with the theoretical expectations.

Upon analysing section 3.5, it was observed that the obtained results were close to the anticipated outcomes. As the factors represented in each section (3.5.1, 3.5.2, 3.5.4, 3.5.5) were varied, the stress concentration factor decreased as intended and predicted. However, in the case represented in section 3.5.3, it was found that the variation of the analysed parameter increased the stress concentration factor, which was expected but not intended. Consequently, it was concluded that the desired effect of increased fatigue resistance was achieved with the variations of the parameters represented in sections 3.5.1, 3.5.2, 3.5.4, 3.5.5.

Regarding the results presented in section 3.4, it was discovered that, contrary to the previous expectations, the outcomes in this case differed from what was anticipated, except for the case represented in section 3.4.4.

A concise explanation of the results can be found in section 3.4.6, while a more comprehensive and detailed explanation is provided in the current section.

During the study of the CFRP strip's behavior, it was observed that the plate deformed, as illustrated in Figure 3.10. This phenomenon arises due to variations in CFRP properties, resulting in a shift in the center of gravity and the eccentricity effect when only one CFRP patch is applied. Consequently, there is an increase in eccentricity, leading to a subsequent increase in bending. As a result, the outcomes in the aforementioned section differ from the initial expectations. In

real scenarios, as discussed in Chapter 4, where cross-sectional areas and moments of inertia are greater, the influence of eccentricity tends to be less significant.

After conducting the present case study, it is evident that the addition of CFRP significantly enhances fatigue resistance. This conclusion provides a foundation for proceeding to the next phase of the analysis, where the behavior of CFRP in an actual case study will be examined, as described in chapter 4. It is crucial to emphasize that the analysis conducted in chapter 4 addresses a relatively unexplored topic, namely the application of CFRP composites in real-world cases, making it a significant challenge.

In this chapter 3, the decision was made to apply the total bounding method in the numerical analysis since it is the method employed in the subsequent chapter for the real case, thus overcoming the challenges associated with modeling and structural analysis.

Chapter 4

Case study: The Várzeas Bridge

4.1 Introduction

Significant progress has been made in the study of fatigue phenomena during the past few decades, mainly in welded and bolted connections. Nonetheless, many riveted bridges that were built without any specific fatigue testing are still in use and are anticipated to do so for the longest possible duration in order to minimise the expenses associated with maintaining railway infrastructure.

Accordingly, there has been an increase in the circulation of heavier trains at faster speeds over time, which contributes to inferior dynamic performance and the accumulation of structural deterioration.

The major goal of this section is to examine the Várzeas bridge, specifically to assess the fatigue safety of the permitted traffic scenarios.

4.2 Description of the Bridge

The Várzeas bridge, under study, is situated in the district of Aveiro, Portugal, part of the international railway line of Beira Alta. The original construction of this bridge dates back to 1882. Notwithstanding, as part of railway network investment initiative, the original structure was replaced in 1958 by the current structure design by the Krupp House.

Commencing with a general analysis of the geometric parameters, the overall length of the structure measures 281 m, characterized by two extreme spans of 50,50 m each and three central spans, each measuring 60 m. The structural system can be delineated into distinct groupings of elements:

- Cross girders join two inverted Warren truss girders, creating the deck and supporting the ballastless railway track;
- The longitudinal elements are connected by three different degrees of longitudinal bracings (inferior, superior, and noise bracings);

- The cross-sectional bracings are linked to the inferior flanges, vertical-posts of the inverted Warren trusses and cross-girders at regular intervals;
- As columns, there are four trusses with a trapezoidal shape and varying heights;
- The railway loadings are also supported by one granite masonry column on the west side and one granite masonry abutment on the east side.

Additionally, on the western side, a 20 m long, simply supported crossings connects the Luso railway station to the Várzeas Bridge. The figure 4.1 is an overall view of some of the mentioned Várzeas Bridge's structural components [74].

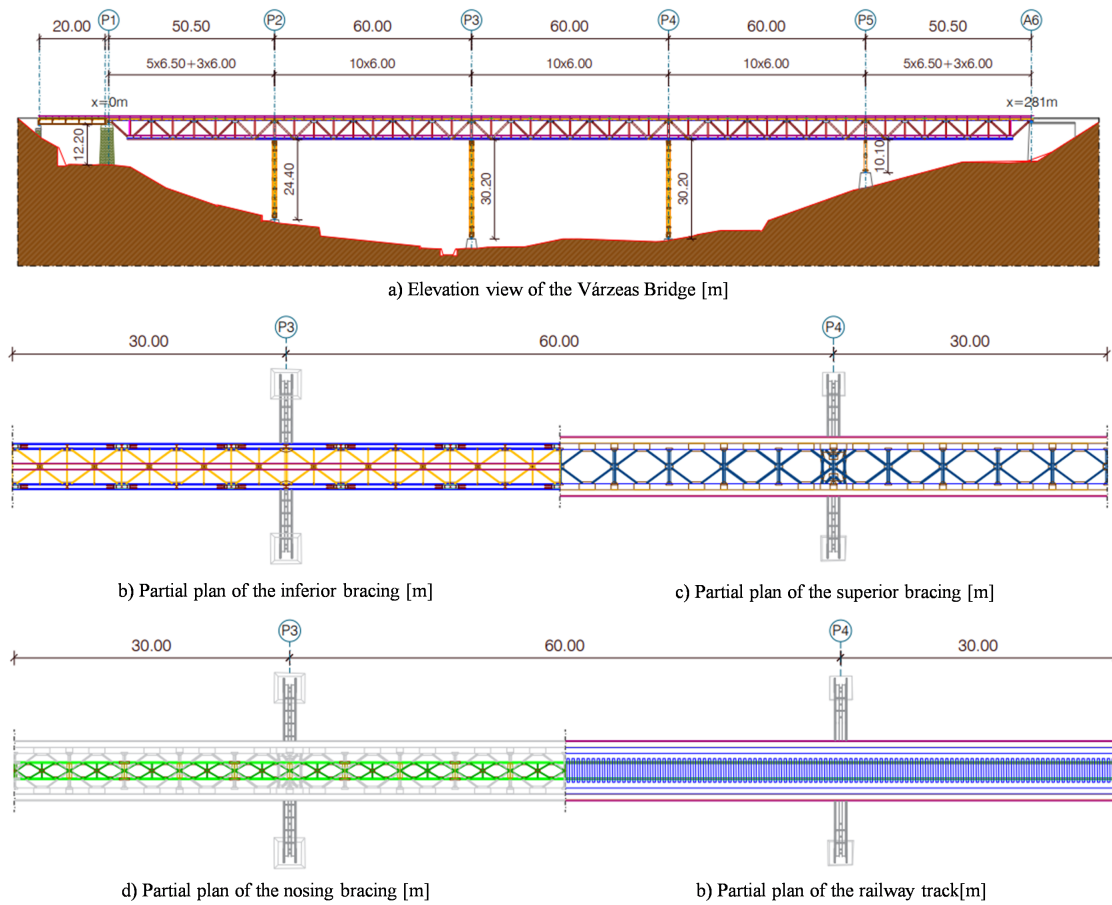


Figure 4.1: Overall view of some of the Várzeas Bridge's structural components, with permission [75, 74]

The fundamental dimensions of the structural system encompass a height of 5.95 m and width of 4.40 m for the two inverted Warren trusses. Additionally, the first and last five girder panels exhibit a length of 6.50 m, while the remaining five panels measure 6.00 m each, resulting in a total length of $5 \times 6.50 + 3 \times 6.00$ m at the extreme spans. As for the vertical elements, the steel columns vary in height from 10.10 m to 30.20 m, whereas the granite masonry column stands tallest at 12.20 m [75, 74].

The upper flanges of the inverted Warren trusses comprise two U-shaped components, each with a height of 400 mm, which are interconnected by a continuous plate measuring 650 mm in

width and 12 mm in thickness. In contrast, the lower flanges exhibit a comparable shape, with a plate thickness of 13 mm, gradually increasing to 20 mm as they approach the columns, spanning a distance of 6 m on each side.

As for the diagonal elements, a standardized cross-section was observed, comprising two U-shaped sections measuring 350 mm in height. Nevertheless, near the truss panels adjacent to the columns, this configuration is modified to a cross-section defined by two U-shaped sections with a height of 400 mm. The vertical posts feature an I-shaped cross-section, measuring 348 mm in height and 297 mm in width. At the truss-to-column connections, these vertical posts are modified to an I-shaped section with a height of 348 mm and width of 560 mm. The cross-girders fulfill the function of supporting the longitudinal stringers beneath the railway track. The cross-girders are composed of I-shaped sections, with a height of 688 mm and a width of 297 mm. The longitudinal stringers, on the other hand, are also constructed using I-shaped sections, measuring 550 mm in height and 200 mm in width.

Likewise, the structural design incorporates three levels of longitudinal bracings, namely the inferior, superior, and nosing bracings. These bracings, as well as the cross-section bracings, are formed using L-shaped, half I-shaped, or U-shaped sections, depending on the specific requirements of each section [74, 2].

The figure 4.2 is a schematic drawing of the cross-section of the Várzeas Bridge, representing what was mentioned.

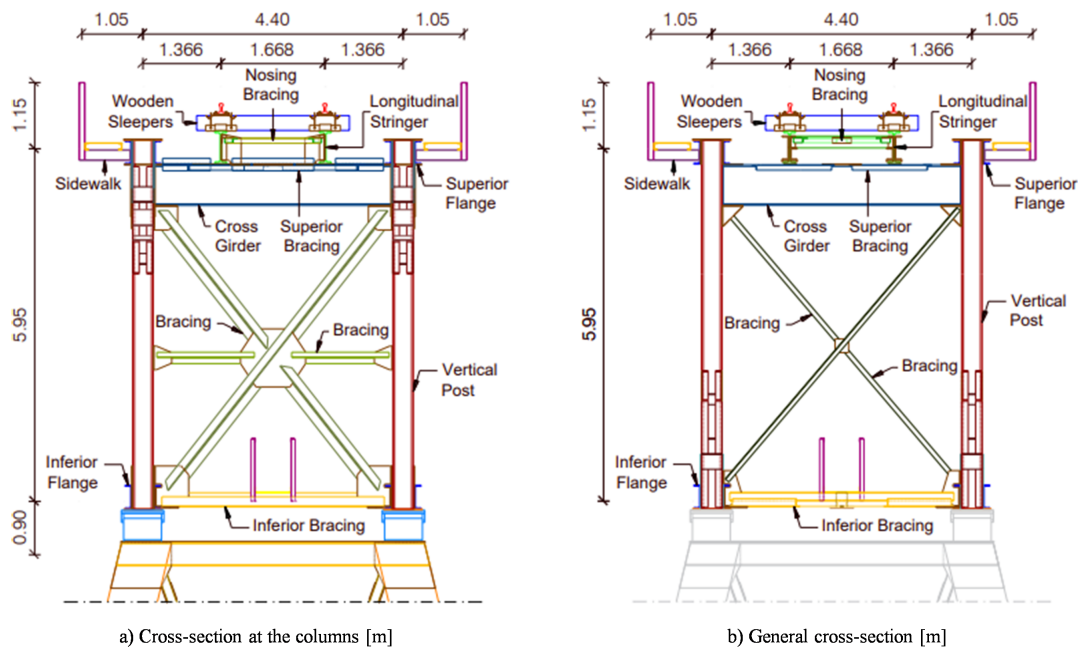


Figure 4.2: Schematic drawings of the cross-section of the Várzeas Bridge, with permission [75, 74]

Certain nodes have a high density of confluent structural components, which results in connections with remarkably intricate geometrical patterns. The union of line elements is established

and levelled using several angles and infill plates, which have a typical thickness of 14 mm. Additionally, a significant amount of rivets were discovered, with nominal diameters falling within two different ranges: the connections between the most crucial structural components (truss flanges, diagonals, vertical posts, cross-girders, and longitudinal stringers) should be between 22 and 32 mm, and the remaining details requiring bracing members should be between 9 and 20 mm.

The metallic bearing supports enable unrestricted rotations in the longitudinal plane, or yy -direction. The longitudinal displacement is likewise free on the west side, allowing for motions brought on by horizontal forces, for instance thermal loading, traction, and braking forces. Furthermore, the longitudinal movement is restricted at the remaining supports. Nevertheless, the east abutment absorbs the majority of forces brought on by horizontal deformations since the metallic columns are flexible [2, 74].

4.3 Detailed analysis of the Várzeas Bridge

Embodied within the illustrious Beira Alta international railway line lies an architectural trussed and riveted structural system. However, this remarkable creation, conceived in 1958, bore the weight of a significant omission: the absence of diligent fatigue assessments. The structural system's available data were gathered as the bedrock for the integrated technique, and a scrupulous visual inspection was artfully layered atop it. These intricate details enable the precise definition of the geometrical and material attributes of the global numerical model, as showcased in figure 4.3 [76].

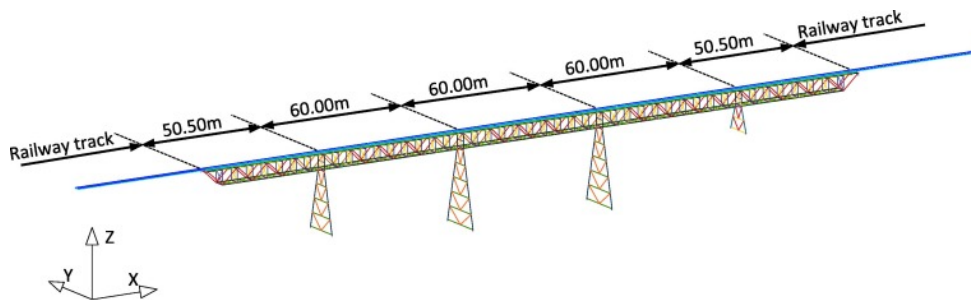


Figure 4.3: Numerical model Várzeas Bridge, with permission [74, 77]

In the realm of structural analysis, reconciling the disparity between the the global scale of structures and the localized fatigue phenomena has been a significant challenge. To address this, international standards propose from stress-life methods, centered on nominal stresses for fatigue assessment, while also factoring in the influence of local stresses within S-N curves. This approach not only offers a comprehensive framework for evaluating fatigue, but also enhances the accuracy and applicability of the assessment process [78, 79, 80, 81].

In the context of fatigue calculations, Horas et al. [76] have proposed a multi-phase methodology, which was applied to a case study involving the Várzeas Bridges. This model utilizes the equivalent stress range method as its primary approach, simultaneously taking into consideration

the linear elastic properties of the materials to comprehensively address the global aspects of the assessment.

To surmount the limitations of global methods, Horas et al. [82, 83] introduced two insightful local approaches for fatigue analysis, involving submodelling techniques leveraged by modal superposition techniques to compute local fatigue quantities, which allow after implementing local fatigue methods. The first involves capitalizing on modal superposition principles to discern intricate structural behavior. The second encompasses the use of local notching methods or Linear Elastic Fracture Mechanics concepts, enabling a comprehensive investigation of crack initiation and propagation phenomena. These innovative methodologies offer a more refined understanding of fatigue mechanisms at localized regions, facilitating more accurate and targeted assessments of critical structural components.

However, employing these calculation strategies across numerous connections may entail a computationally inefficient process. Nevertheless, it is important to acknowledge that these local fatigue approaches represent advanced methodologies that can be leveraged effectively once conservative normative global methods have been implemented. These intricate techniques serve as invaluable tools in probing the nuanced behavior of critical structural components, offering a more refined and accurate understanding of fatigue phenomena at localized levels [76].

As previously mentioned, to establish the range of acceptable nominal stresses under the considered load scenarios, including the standard and heavy load scenarios specified in the EN 1991-2 Eurocode, an assessment of fatigue resistance was conducted. This assessment involved the utilization of Eurocode detail curve 71, which, while typically intended for welded connections, has been proposed for riveted connections by various experts in the field. A comprehensive set of thirteen detail types, encompassing both main and secondary details (designated as D.1 to D.13), was established. It's crucial to acknowledge that fatigue evaluations have been conducted for all structural details. Nevertheless, for the simplification in this study, the results examined for the detail exhibiting the highest μ_{FDF} values, for the critical detail associated with diagonal D.5. This emphasis underscores the pivotal role of this specific detail in the analysis.

Upon meticulous examination, it was revealed that the diagonals in the bridge assumed primordial importance due to their pivotal role in bearing the load capacity, resulting in elevated levels of nominal stress. Consequently, a prudent course of action involved fortifying the cross-section of these significant structural elements adjacent to the abutments with 2UPN400, as opposed to the standard 2UPN350 employed in the general section, a parameter derived from the original design.

Horas et al. [76] propose a fatigue analysis divided into three phases, with results already available. Phase 1 initiates the study by applying simplified methods over a projected service life of 100 years, as depicted in figure 4.4. Upon closer examination of the figure 4.4, it became evident that the bridge's symmetrical configuration led to the identification of 92 details scrutinized, where each bar in the figure represents a detail of the bridge. These connections exhibited a μ_{FDF} exceeding 1.00, highlighting their vulnerability and demanding attention.

Phase 2 involves applying linear damage accumulation over a projected service life of 100 years with heavy traffic, following Eurocode 3 guidelines [8]. Figure 4.5 presents the results

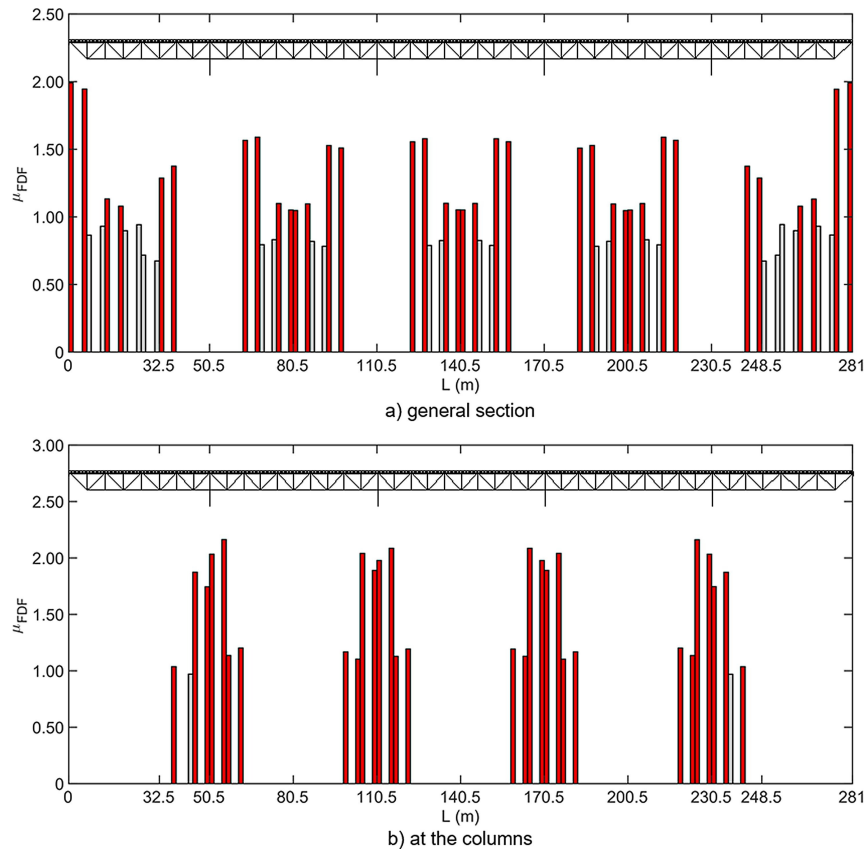


Figure 4.4: D.5, Fatigue Damage Factor (μ_{FDF}): diagonals, with permission [74, 77]

related to the second phase of the proposed methodology, with assumptions consistent with the results obtained in figure 4.4, enabling a comparison between the two sets of results. An insightful analysis of figure 4.4 brought to light that among the 92 details scrutinized, a noteworthy 66 riveted connections were identified as susceptible to fatigue assuming the normative Heavy traffic scenario, figure 4.5.

Given this context, it is possible to proceed to phase 3, the primary focus of this research, which entails the application of CFRP to enhance the most critical structural components.

Upon a comprehensive comparison of the outcomes presented in figures 4.4 and 4.5, a recurring pattern emerged, indicating that the details most susceptible to fatigue were consistently situated in close proximity to the columns and end supports during both phases of evaluation.

Recognizing the significance of transitioning from the global perspective to a more localized focus, specifically pertaining to the intricacies of fatigue phenomena, dedicated efforts were undertaken to enhance and refine the pertinent dataset.

Through a scrupulous analysis of intricate details, a complete assessment was conducted to discern the precise geometry and positioning of the rivets. This comprehensive examination allowed for a characterization of the riveted length and consequently facilitated the refinement of the global model, enabling the development of a more sophisticated and precise local model.

Considering this information, and with knowledge that the specific detail is situated at $x=104.5\text{m}$,

a refinement was carried out in the initial 15m of the global model, focusing on enhancing the sub-modeling relationship for a more precise representation. This refinement was initiated during the advanced stages of the fatigue analysis. This enhancement in modeling aims to establish a more accurate submodeling relationship for the critical detail under investigation, as depicted in the figure 4.6.

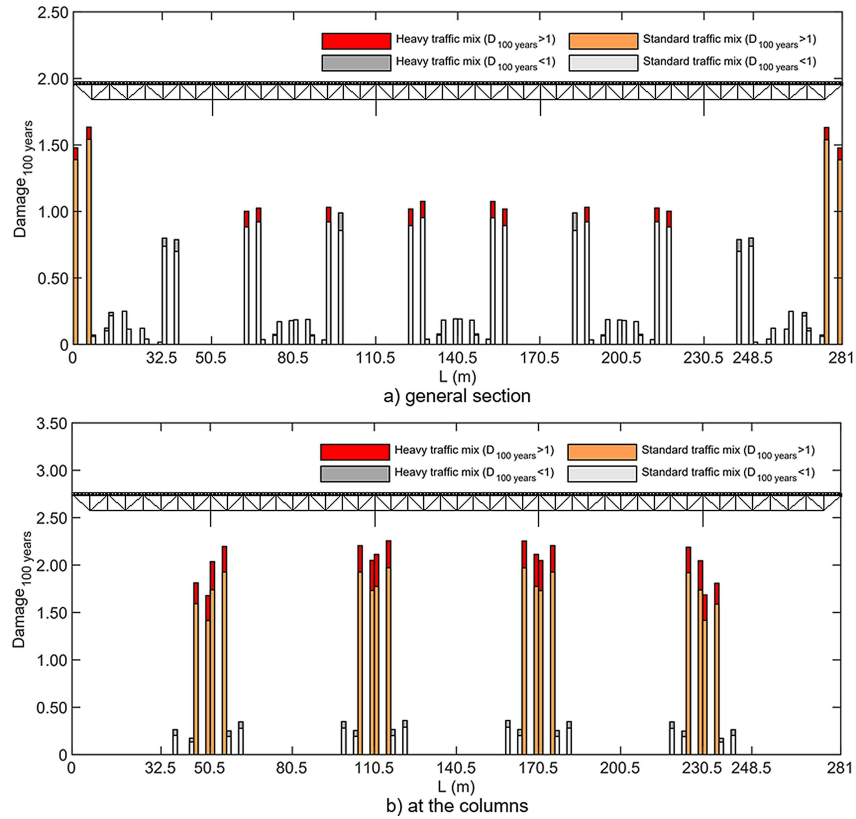


Figure 4.5: D.5, Fatigue Damage Factor (μ_{FDF}): diagonals, with permission [74, 77]

Figure 4.6 a) illustrates the refinement incorporated into the global model, featuring shell elements known as SHELL181 [70], which are connected to the line elements using line-shell connections through multipoint constraints. Additionally, it is important to note some of the boundaries associated with the designed volumetric model, as depicted in figure 4.6 b) [74, 84].

In the volumetric model, 20-node volumetric elements (SOLID186 in [70]) were employed to represent the steel elements, including the 44 rivets (22 per side) that connect the reinforcement plates. The only exception to the local bracing is in the column section, which is modeled using beam elements (BEAM188 [70]). Speaking of the local geometry, two reinforcement plates were identified, providing alternative load transfer paths, as shown in figure 4.6 c) and d). The normal and frictional contacts between all steel plates were simulated using the ANSYS contact tool CONTA174-TARG170 [70].

The typical heavy traffic mix was utilized as a reference due to the limited availability of precise information about the actual traffic on the bridge. The movement of these trains induces

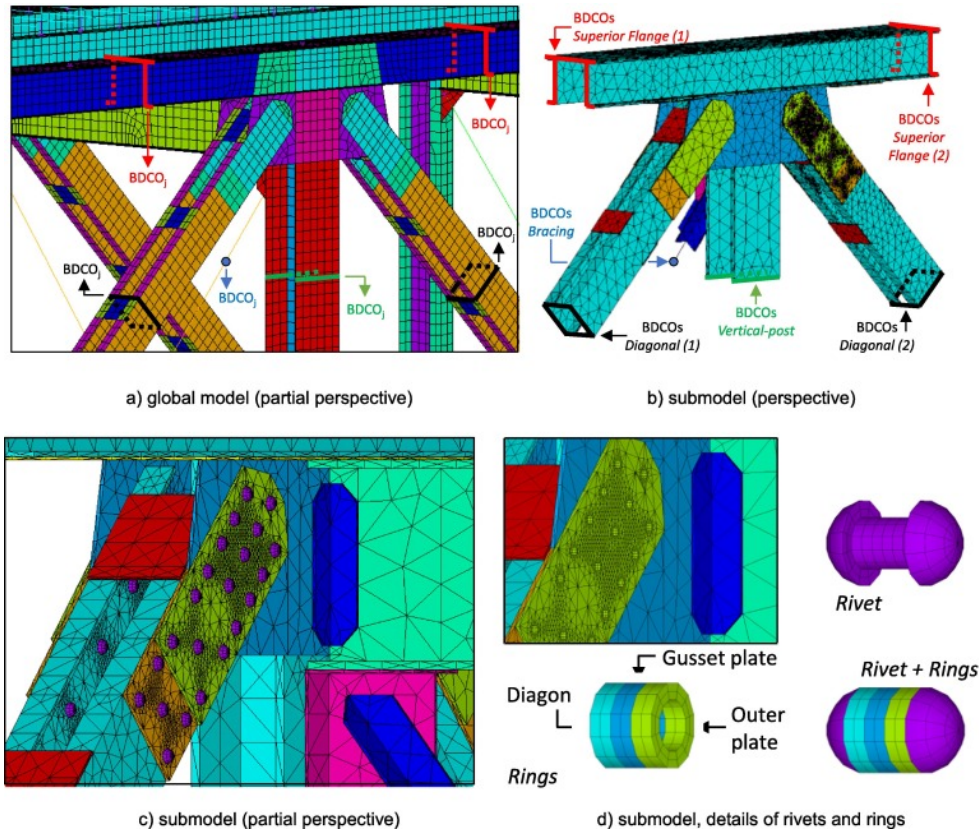


Figure 4.6: Numerical model Várzeas Bridge, with permission [76]

dynamic responses at the local level, which are influenced not only by the bridge's global characteristics but also by the local behavior of the load transfer mechanism.

To validate the multiscale connection between the local and In order to validate the multiscale connection between the refined local and global models, the critical locations susceptible to cracking initiation were pinpointed. This validation process involved conducting an experimental campaign under the influence of a known train load, and subsequently, the obtained results were compared with the numerical findings, demonstrating a significant level of agreement [74]. Following the validation of the model relationship, the precise location of the hot-spot was determined. As anticipated in the absence of a construction flaw, the most crucial areas were those located in the holes connected to the rivets.

$$BDCOs_{\varphi}(t) = BDCOs_{sw} + \left[\sum_j BDCOs_j \cdot Y_j(t) \right] / [1 + \varphi'] \cdot [1 + 0.5(\varphi' + 0.5\varphi'')] \quad (4.1)$$

Specifically, the rivet-related contacts introduce interference with the response at the critical point for crack initiation. This interference impacts the local stress state in a nonlinear manner, necessitating the use of modal superposition for the displacement fields of the boundary condition ($BDCOs_{\varphi}$) and establishing the submodeling relationship in the time domain. This approach aligns

with the recommendations outlined in standard EN 1991-2 [85], where equation 4.1 details the calculation of these boundary conditions using modal superposition. It is assumed that the inertial forces generated within the model are considerably lower than the elastic forces applied to the boundaries when equation 4.1 is applied.

Equation 4.1 clarifies that existing local contacts exert an influence on the local response at critical locations. To account for this influence, amplified boundary displacement fields in the time domain, denoted as $BDCOs_\phi$, were calculated. These fields were appropriately amplified for integration into the submodel.

Initial calculations unveiled some multi-axial aspects in the local stress results, with the pre-dominant value being associated with the axial direction of the diagonal [84, 74].

To assess the magnitude of the local stresses, a conservative approach was adopted by calculating the results of the Von Mises stresses, denoted as σ_{VM} . Figure 4.7 displays the stress values at the critical point, which is the rivet with the highest local stresses for crack initiation in the marked rivet hole, where fatigue life was theoretically calculated to be infinite, which contrasts with the results obtained in phases 1 and 2. Despite these findings, the decision was made to further investigate the impact of reinforcement for this specific detail by introducing a CFRP patch. It is also essential to mention that this analysis takes into account the presence of heavy traffic vehicles, such as FT5 (Fatigue Train Type 5), as an example [85] As evident from the results, the Von Mises stress exceeds the yield stress ($f_{yd} = 355$ MPa) for FT5, leading to a local plasticity phenomenon.

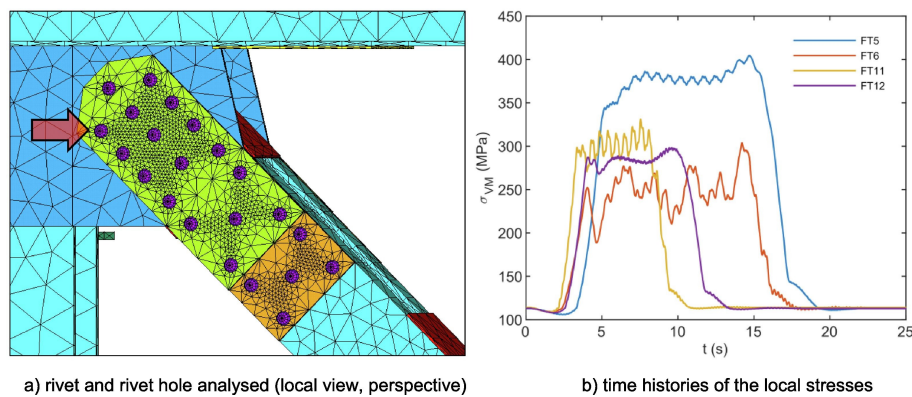


Figure 4.7: Time histories of the local Von Mises stresses for the considered fatigue trains, with permission [84, 74, 86]

The integration of global and local approaches to fatigue offers new possibilities for investigating various geometries composed of different materials. This innovative methodology allows for a comprehensive analysis of fatigue issues, particularly with the growing demand from increasing traffic. It provides a systematic way to assess fatigue in structures integrated into the railway network.

4.4 Fatigue analysis of a critical detail in Várzeas Bridge

Upon conducting an extensive analysis of the case study involving the Várzeas Bridge, it becomes feasible to undertake a more precise analysis. This entails placing a CFRP patch within the previously mentioned critical zone and scrutinizing the variations in Von Mises stress.

In the current analysis performed using *ANSYS*, the previously mentioned approach was employed, involving the utilization of *CONTA174-TARG170* element contacts, being a technique based on total bonding contacts. The visual representation, as shown in the figure 4.8, depicts displacement fields that exhibit continuity, underscoring the effectiveness of the established contacts. Hence, it becomes feasible to apply one CFRP patch, despite its more intricate geometry, without necessitating alterations to the numerical and modeling analysis. The properties of CFRP used in this context are consistent with those presented in chapter 3, as detailed in table 3.2.

The figure 4.8 represents the displacements corresponding to the moment when the local Von Mises stress reaches its maximum value. This critical step involved utilizing the maximum load and the heaviest train configuration, serving as a reference for assessing the effectiveness of applying the CFRP patch.

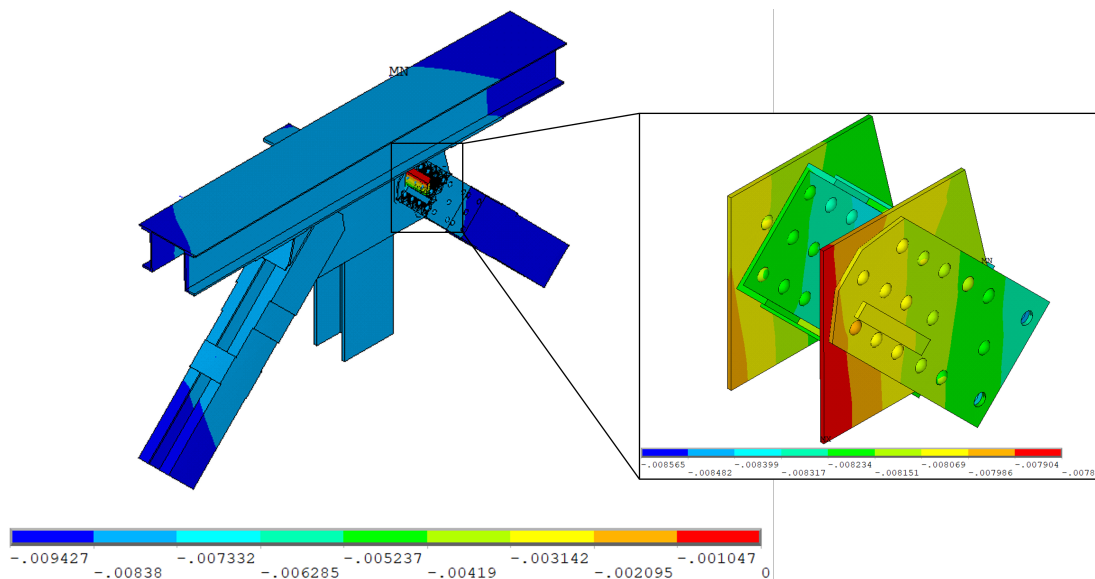


Figure 4.8: Riveted Submodel: displacement field

Within this section, the exploration involves varying CFRP thicknesses at three different values: 0.005 m, 0.010 m, and 0.015 m, in close proximity to the critical detail, as well as the variation of the CFRP patch width to the maximum value. This examination aims at providing insight on how the presence of the CFRP patch influences the behavior of the fatigue-sensitive zone. Concerning the properties of CFRP, the choice was made to uphold the attributes specified in the table 3.2, with adjustments being limited to essential parameters.

4.4.1 Submodel analysis without CFRP patch

For the present section, the focus transitions to initiating potential analyses on the submodel without the presence of the CFRP patch. This preliminary stride establishes the basis for forthcoming comparative assessments. To establish a reference case for comparison with other results, the examination commenced by scrutinizing variations in the Von Mises stress concerning the scenario where a CFRP patch is not applied.

Figure 4.9 presents a contour plot extracted from the ANSYS software, illustrating the crucial detail. This visual representation highlights the location of maximum Von Mises stress incidence within the rivet. By interpreting the scale provided in the rivet diagram, it becomes evident what the value of σ_{max} represents. Nevertheless, it becomes evident that σ_{max} peaks 344 GPa, with an average value equal to 291.5 GPa calculated through the thickness, simulating a thru crack. It should be noted that this value is related only to the loading of fatigue train number 5, not including the self-weight, which is relevant to evaluate the crack initiation phase, but not indispensable to evaluate the impact of the CFRP on the stress field.

Subsequent analyses involve the introduction of the CFRP patch, with adjustments to its thickness. A comparison is made between the calculated values and the reference situation related to the stress field without the influence of the CFRP patch, for example, the stress map represented on figure 4.9.

It's worth noting that the analysis of the rivet in figure 4.9 reveals the most critical component lies within the rivet itself, specifically the intermediate plate referred to as the gusset plate. Nevertheless, due to this fact, reinforcement is not applied directly to this critical region since there are two external plates, referred to as cover plates.

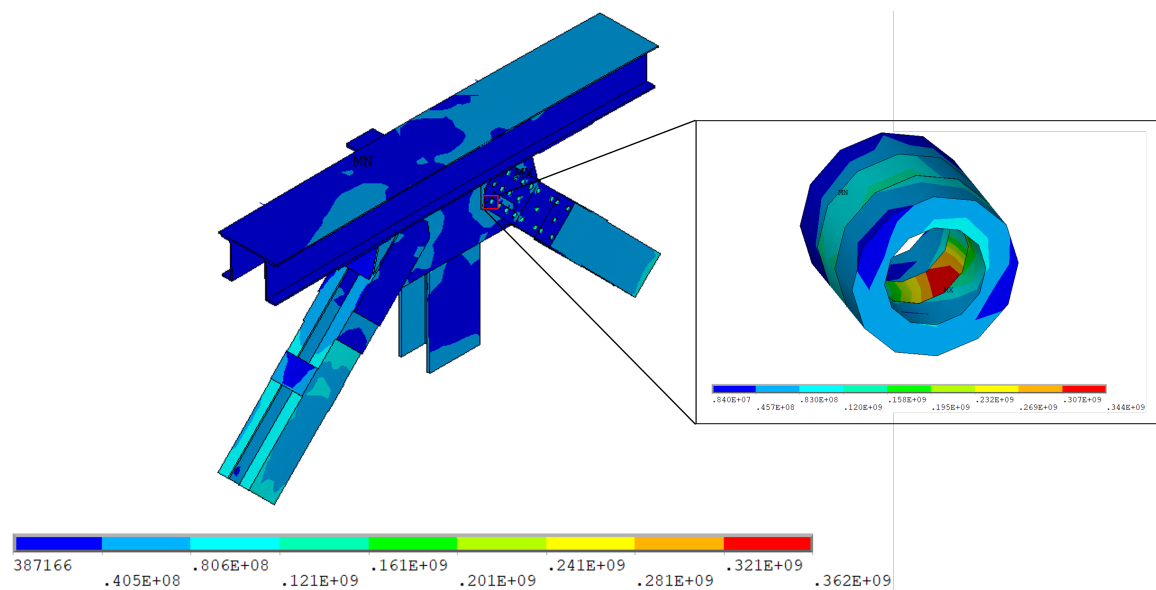


Figure 4.9: Von Mises stress analysis without CFRP patch at the critical detail

4.4.2 Submodel analysis with a CFRP patch of 0.005 m of thickness

Following the completion of the reference analysis, the attention shifts to the initial scenario, which is to examine the behavior of the submodel upon the application of a CFRP patch with an initial thickness of 0.005 m.

Table 4.1 and figure 4.10 display the parameters assigned to the CFRP patch being utilized.

Table 4.1: Parameter values for CFRP patch of 0.005 m of thickness

Parameters	[m]
t	0.005
W	0.050
L	0.255

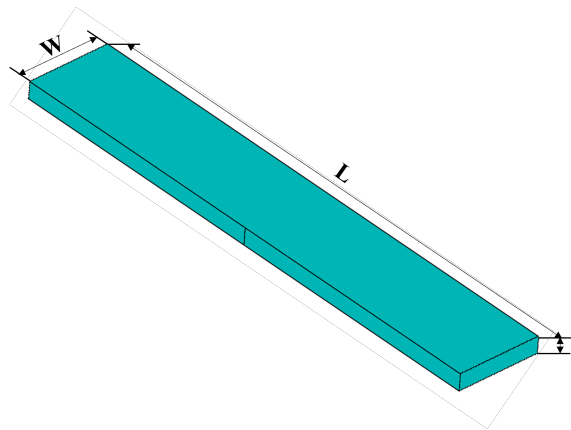


Figure 4.10: Parameters assigned to the CFRP patch

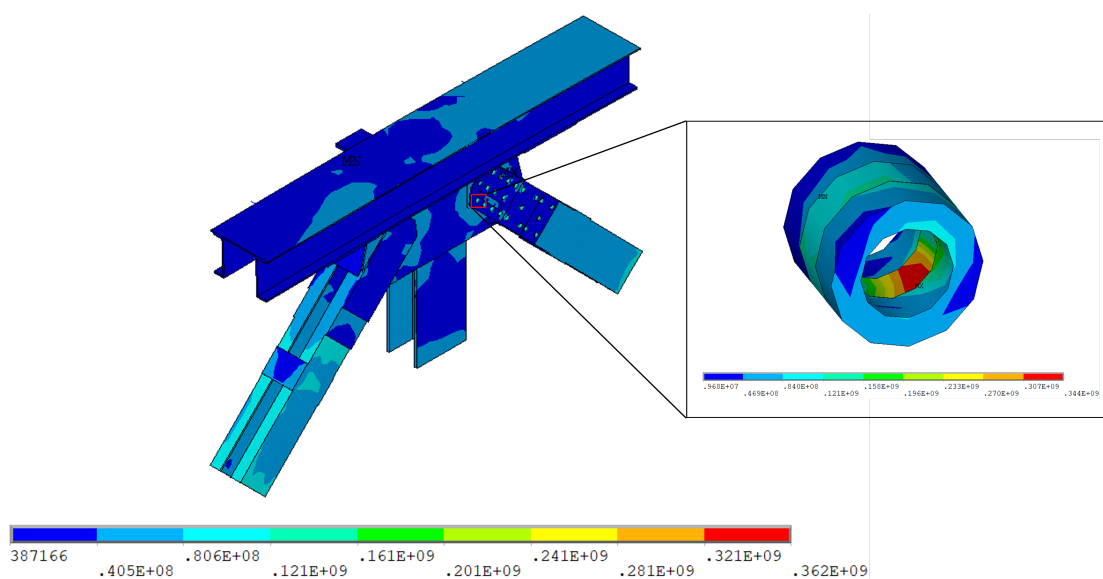


Figure 4.11: Von Mises stress analysis at critical detail with a CFRP patch of 0.005 m thickness

Figure 4.11 visually illustrates the integration of the CFRP patch adjacent to the critical detail, specifically near the rivet. Similar to the previous methodology, it is employed the *ANSYS* software to generate contour plots depicting the Von Mises stress outcomes. Table 4.1 and figure 4.10 display the parameters assigned to the CFRP patch being utilized.

Upon careful examination of figure 4.11, it becomes evident that the maximum Von Mises stress attained is 344 GPa, however, as mentioned earlier, this maximum stress is very localized, and the average stress calculated throughout the crack remains at 291.5 GPa. This value does not carry substantial importance and does not significantly deviate from the previously obtained results.

4.4.3 Submodel analysis with a CFRP patch of 0.010 m of thickness

In this section, a parallel analysis to the previous section is undertaken, with the singular modification being the adjustment of the CFRP patch thickness to 0.010 m. This modification is visually represented in Table 4.2 and Figure 4.10.

Table 4.2: Parameter values for 0.010 m of thickness

Parameters	[m]
t	0.010
W	0.050
L	0.255

Considering this, Figure 4.12 visually presents a contour plots from the mentioned software, showcasing a color scale that corresponds to the maximum Von Mises stress within the critical detail.

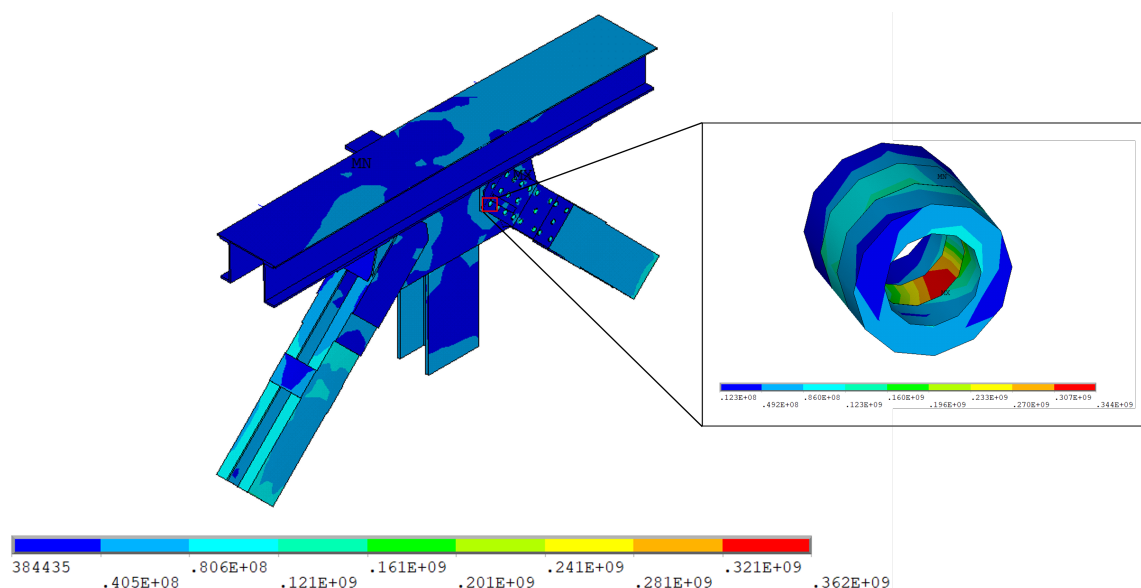


Figure 4.12: Von Mises stress analysis at critical detail with a CFRP patch of 0.010 m thickness

In this context, it becomes evident that the maximum Von Mises stress remains consistent at 344 GPa, aligning precisely with the values obtained from the previously analysed cases. Nevertheless, as previously noted, this peak stress is concentrated at a specific point, while the average stress calculated across the crack area maintains a value of 291.5 GPa.

4.4.4 Submodel analysis with a CFRP patch of 0.015 m of thickness

Finally, this section delves into the analysis of the CFRP patch with a thickness of 0.015 m.

Upon examining figure 4.13, it becomes evident that the implementation of the CFRP patch aligns with the geometric parameters outlined in table 4.3 and figure 4.10. This implementation was executed using the ANSYS software, from which the Von Mises stresses were extracted. Subsequently, a contour plots depicting stress levels associated with each point was generated, as shown in Figure 4.13.

Table 4.3: Parameter values for 0.015 m of thickness

Parameters	[m]
t	0.015
W	0.050
L	0.255

That being said, upon analyzing figure 4.13, it is evident that the maximum Von Mises stress recorded is 343 GPa. This observation confirms that, in comparison to the previously examined cases, this stress level is approximately equal. However, this reduction is not substantial, as anticipated. As mentioned earlier, this maximum stress is localized, with the average stress throughout the crack remaining constant at 291.5 GPa.

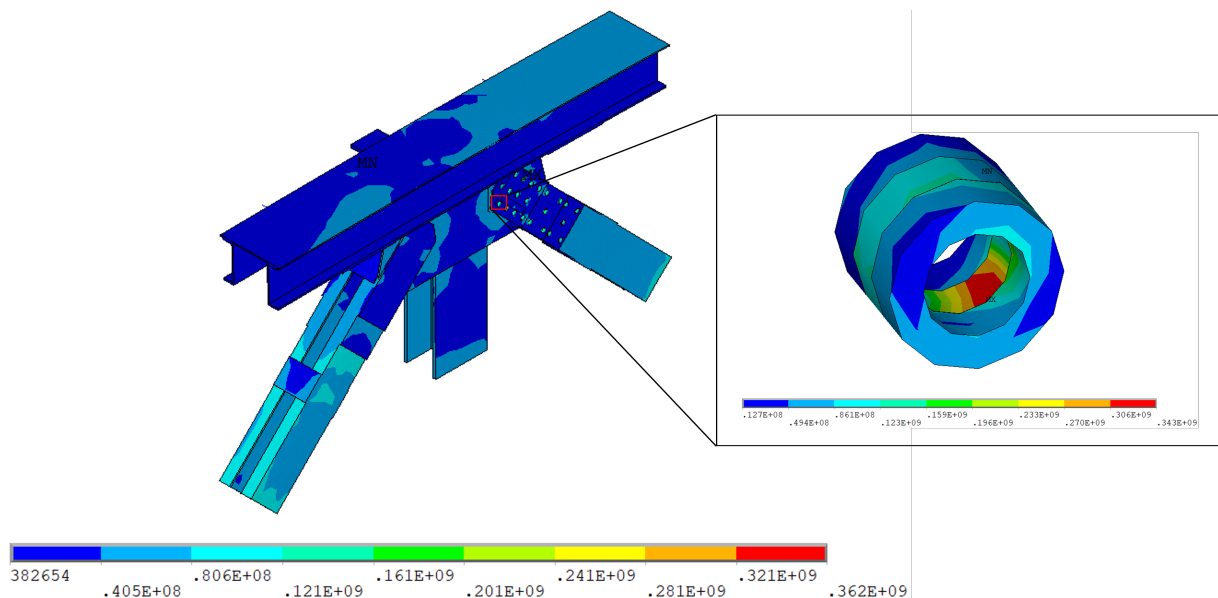


Figure 4.13: Von Mises stress analysis at critical detail with a CFRP patch of 0.015 m thickness

4.4.5 Submodel analysis with a CFRP patch with the maximum width

After conducting an extensive series of analyses, encompassing a range of different thicknesses for the CFRP patch, it was established that these variations failed to yield any groundbreaking or stress reductions. Consequently, a strategic decision was reached to further investigate the most extreme scenario, characterized by the application of the maximum available thickness and the utilization of the CFRP patch's maximum allowable width between the two rows of rivets. This deliberate choice aimed to explore the outer limits of the CFRP patch's performance capabilities and its potential impact on the structural system under consideration.

The table 4.4 includes the parameters assigned to the CFRP patch, with the maximum width spanning from one rivet to the other.

Table 4.4: Parameter values for the maximum width

Parameters	[m]
t	0.015
W	0.075
L	0.255

Utilizing the ANSYS program, we obtained the maximum Von Mises stresses for the most critical rivet, visualized through a contour plots in the 4.14 figure.

Having said this and after a thorough analysis of the results, it is evident that no ground-breaking findings have emerged. The maximum stresses observed in the most critical detail are approximately 343 GPa, aligning closely with the previously obtained results. Nevertheless, as previously discussed, this maximum stress is localized, while the average stress calculated across the crack consistently measures 291.5 GPa.

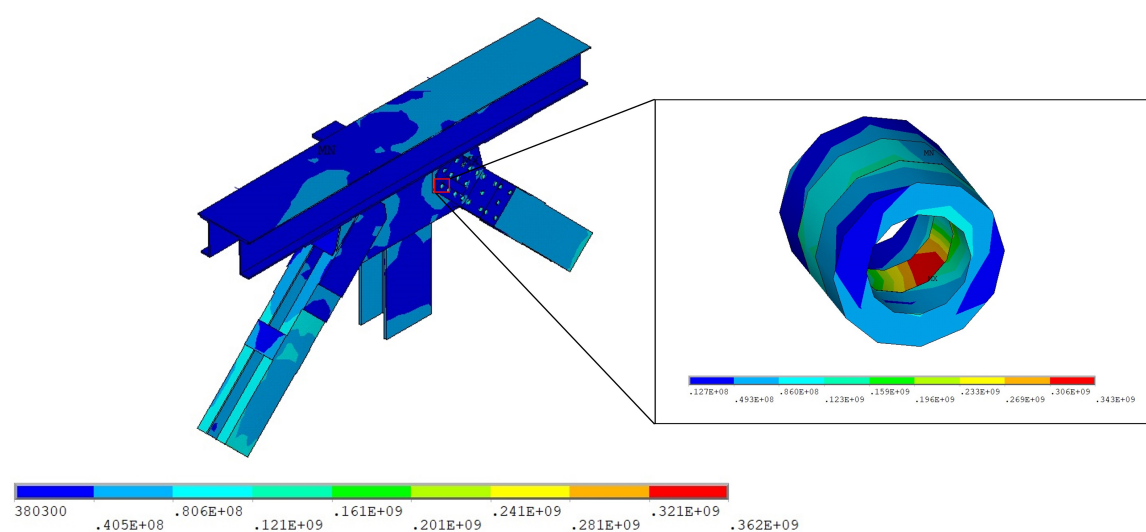


Figure 4.14: Von Mises stress analysis at critical detail with a CFRP patch with the maximum width

To gain a clearer understanding of the critical detail's location, the figure 4.15 illustrates that the critical detail is situated on the Gusset plate. However, the reinforcement is positioned on the outer plate and is not as pronounced at the critical detail since it cannot be directly applied.

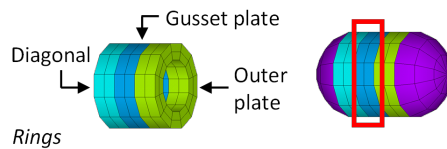


Figure 4.15: Detail of the critical zone

4.5 Concluding remarks

In this chapter, a fatigue assessment of the pivotal connection was conducted. This connection pertains to the rivet depicted in figure 4.7.

As the central objective of this study revolves around prolonging the service life of railway bridges through an augmentation in fatigue resistance, considering that fatigue stands as a primary contributor to structural degradation, a strategic intervention involved the incorporation of a CFRP patch adjacent to the critical detail.

To ensure the attainment of dependable outcomes, an initial Von Mises stress analysis was conducted on the submodel without the integration of the CFRP patch. This preliminary analysis aimed to ascertain the influence brought about by the CFRP patch following its implementation.

The findings of this analysis are outlined in section 4.4.1, wherein it was deduced that in the absence of the CFRP patch, the critical detail experiences a maximum Von Mises stress of approximately 344 GPa, as depicted in figure 4.9, nonetheless, the most crucial stress value is the average stress, which is 291.5 GPa. In light of this, it was anticipated that the incorporation of a CFRP patch would lead to a reduction in the maximum stress at the critical detail, specifically at the rivet. This phenomenon is dissected further in sections 3.5 and 3.4, in a simpler case.

Sections 4.4.2, 4.4.3, and 4.4.4 elucidate the analyses pertaining to the incorporation of the CFRP patch within the submodel, each involving distinct thicknesses. The purpose behind these analyses is to assess whether increasing the thickness confers any advantages. Subsequently, through the execution of simulations using *ANSYS* software, corresponding contour plots were generated for each analysis. These visual representations are showcased in figures 4.11, 4.12, and 4.13.

After conducting analyses for various thicknesses of the CFRP patch, it is chose to pursue a more extreme scenario in which applied the maximum available thickness and the CFRP patch's maximum allowable width. The objective of this analysis was to determine whether, under these extreme conditions, could achieve more innovative results through reinforcement. Once again, it was observed that the maximum Von Mises stresses obtained remained quite similar for the gusset as the reinforcement was applied directly on side cover plates. This led to the conclusion that,

in the specific detail under scrutiny, the application of a CFRP patch did not fulfill its intended purpose, namely, achieving the desired reinforcement.

Furthermore, it's worth noting that despite minimum variations in the maximum Von Mises stresses obtained across different analyses, ranging between 343 and 344 GPa, however, the analysis of the average stress obtained remained constant at 291.5 GPa, which resulted from the clearance gap assessment.

This observed behavior can be attributed to the structural configuration. Specifically, the critical detail is situated within the reinforcing plate, while the application of the CFRP patch occurs on the outer plate, as illustrated in figure 4.6 (d) and 4.15. Consequently, the obtained results failed to meet expectations, primarily due to the critical zone—where the optimal positioning of the CFRP patch is intended—being positioned beneath another plate, with a separation of approximately 14 mm.

In this manner, a comprehensive exploration into the pragmatic implementation of a CFRP patch within a real-world context.

Chapter 5

Conclusions

The central focus of this dissertation lies in evaluating the fatigue-induced damage of a pivotal detail within an actual railway bridge, subsequent to the incorporation of a CFRP patch. The significance of fatigue within steel structures gains prominence when dissecting the analysis of railway bridges. This phenomenon stands as a principal contributor to structural deterioration, often culminating in relevant degradation of the structural integrity.

Given the unprecedented nature of this case study within a real-world context, a decision was made to initiate the exploration by assessing the behavior resulting from the integration of a CFRP patch within a rectangular plate that features a central hole.

With this context in mind, the analysis of the simple case was bifurcated into two distinct segments: the first aimed at dissecting the effects of integrating two CFRP patches adjacent to the critical detail; and the second aimed at scrutinizing the impact of introducing a solitary one-sided CFRP patch in close proximity to the same critical detail. Upon conducting both of these outlined case studies, a discernible pattern emerged: the scenario involving two sided CFRP patches yielded the most favorable and anticipated response.

Conversely, when considering the single-patch scenario, it was apparent that the disparity between the expected and observed results could potentially be attributed to the presence of only one CFRP patch. This asymmetric placement potentially triggers shifts in the center of gravity as modifications are introduced, contributing to the observed differences.

Nevertheless, despite observing substantial changes during the various analyses involving a CFRP patch on the steel plate with a central hole, it becomes evident that these alterations, including the shift in the center of gravity, exert a comparatively less significant influence on a real-world section like the one examined in the bridge. As a consequence, the significance of the results derived from section 3.4 is somewhat diminished in the broader context.

With these considerations in mind, it became evident that the application of a CFRP patch produced tangible benefits in enhancing fatigue resistance. This pivotal insight paved the way for delving into the real case study: the Várzeas Bridge. Here, the objective was to ascertain the potential impact of implementing a CFRP patch adjacent to a critical detail.

Chapter 4 serves as an in-depth exploration of the real case study, wherein an exhaustive analysis of the existing bridge information was conducted. This comprehensive assessment led to the identification of the critical detail situated on the defined diagonal D.5, specifically a rivet. Following the determination of this most fatigue-prone detail, the strategic insertion of a CFRP patch was undertaken to gauge its potential positive influence [76].

To ensure a more accurate perception, the thickness of the CFRP patch was systematically varied. This process is detailed in section 4.4.1, where the initial analysis is presented without the CFRP patch. Further exploration occurs in section 4.4.2, where the CFRP patch is introduced with a thickness of 0.005 m; in section 4.4.3, where the thickness is adjusted to 0.010 m; and finally in section 4.4.4, where the thickness is further modified to 0.015 m.

After conducting the aforementioned analyses, the results obtained unveiled a perplexing revelation contrary to the initial expectations. Specifically, the implementation of a CFRP patch, which should theoretically exert a positive influence as demonstrated in sections 3.5 and 3.4, surrendered results that fail to yield the desired outcome. Rather than witnessing the anticipated decrease in maximum stress within the critical detail, the results indicated a lack of change in stress levels. Consequently, an attempt was made to alter the patches thickness in the hopes of generating more advantageous outcomes. However, this endeavor produced similar results, demonstrating minimal alterations.

In light of these unanticipated outcomes, the quest for an explanation that could substantiate these findings became imperative. Consequently, it was established that the critical detail in question resided on diagonal D.5, encompassing three plates: the diagonal, the gusset plate, and the outer plate. Upon closer analysis, it became evident that the fatigue-critical region was primarily concentrated within the gusset plate's. Therefore, when the CFRP patch was implemented on the outer plate, its efficacy was predominantly felt on this plate, rendering it challenging to effectively influence the critical detail. While this particular case study may not have submit groundbreaking results, it's important to acknowledge that the implementation of a CFRP patch in a different detail within a real-world example could still potentially achieve the desired outcomes.

Chapter 6

Future Developments

The introduction of novel approaches for predicting fatigue life suggests the potential development of numerous numerical models and computational algorithms. These advancements could serve as the foundation for substantial future research aimed at evaluating the fatigue endurance of existing bridges and subsequently enhancing their performance.

In light of the present study, a number of valuable recommendations are proposed for future investigations:

- Through parametric research, investigate how various CFRP material characteristics, patch widths, and orientations affect the effectiveness of the applied patch;
- Explore alternative geometries for actual bridge components;
- Generate quantitative data to support the use of CFRPs in real-world bridge applications;
- Conduct on-site experimental trials involving the application of CFRP patches to evaluate their influence on localized stress factors;
- Perform a comparative analysis between numerical simulations and empirical findings;
- Formulate practical recommendations and guidelines for the effective utilization of CFRPs in real bridge components.

After suggesting future projects, the proposal is submitted to FEUP research groups, allowing them to further develop these initiatives within the scope of European or national projects

References

- [1] Alan C.G. Hayward. The construction of railway bridges then and now. *International Journal for the History of Engineering and Technology*, 84:59–87, 2014.
- [2] Cláudio Carlos Silva Horas. *Integrated methodology for fatigue life prediction of existing metallic railway bridges*. PhD thesis, FEUP, 2022.
- [3] UIC international union of railways. Sustainability. Available at = <https://uic.org/sustainability/>, accessed at March 2023.
- [4] Mobility and transport. Infrastructure. Available at = https://transport.ec.europa.eu/transport-modes/rail/infrastructure_en, accessed at April 2023.
- [5] CP: Comboios de Portugal. Chronology: Cp - comboios de portugal. Available at = <https://www.cp.pt/institucional/en/railway-culture/cp-history/time-line>, accessed at March 2023.
- [6] Inês de Azevedo Isidoro, Teresa Marat-Mendes, and Vera Regina Tângari. The portuguese railway in time and space—mapping phases of growth, stagnation, and decline (1845–2015). *Planning Perspectives*, 33:363–384, 2018.
- [7] Dicionário de Engenharia Civil " Fadiga. Fadiga. Available at = <https://www.engenhariacivil.com/dicionario/fadiga>, accessed on April 2023.
- [8] The European Union. En 1993-1-9: Eurocode 3: Design of steel structures - part 1-9: Fatigue. 2005.
- [9] Lili Hu, Peng Feng, and Xiao Ling Zhao. Fatigue design of cfrp strengthened steel members. *Thin-Walled Structures*, 119:482–498, 2017.
- [10] Anis Mohabeddine, José A.F.O. Correia, Pedro Aires Montenegro, and José Miguel Castro. Fatigue crack growth modelling for cracked small-scale structural details repaired with cfrp. *Thin-Walled Structures*, 161, 2021.
- [11] Qaidar H Tawfik, Wana (Karu, and) Karunasena. Use of cfrp for rehabilitation of steel structures: a review. *Proceedings of the 2010 Southern Region Engineering*, 2010.
- [12] Guilherme Alencar, Abilio De Jesus, José Guilherme Santos da Silva, and Rui Calçada. Fatigue cracking of welded railway bridges: A review. *Engineering Failure Analysis*, 104:154–176, 05 2019.
- [13] Bruno Pedrosa, José A.F.O. Correia, Carlos Rebelo, Grzegorz Lesiuk, Abílio M.P. De Jesus, António A. Fernandes, M. Duda, Rui Calçada, and Milan Veljkovic. Fatigue resistance curves for single and double shear riveted joints from old portuguese metallic bridges. *Engineering Failure Analysis*, 96:255–273, 2019.

-
- [14] David Broek. *Elementary engineering fracture mechanics*. Springer Netherlands, 1982.
- [15] Vladimir V. Bolotin. *Mechanics of fatigue*. CRC Press, 1999.
- [16] Andreas Taras and Richard Greiner. Development and application of a fatigue class catalogue for riveted bridge components. *Structural Engineering International*, 20:103 – 91, 2010.
- [17] X. Ye, Y. Su, and Jianping Han. A state-of-the-art review on fatigue life assessment of steel bridges. *Mathematical Problems in Engineering*, 2014:1–13, 2014.
- [18] Wolfgang Fricke. Fatigue analysis of welded joints: State of development. *Marine Structures*, 16:185–200, 2003.
- [19] D. Radaj, C.M. Sonsino, and W. Fricke. *Fatigue Assessment of Welded Joints by Local Approaches, Second Edition*. Woodhead Publishing in materials. Taylor & Francis, 2006.
- [20] Pizhong Qiao and Mijia Yang. Fatigue life prediction of pultruded e-glass/polyurethane composites. *Journal of Composite Materials*, 40:815–837, 2006.
- [21] Lufan Zhang, Boshi Jiang, Pengqi Zhang, Heng Yan, Xiangbo Xu, Ruizhuo Liu, Jingjing Tang, and Caixia Ren. Methods for fatigue-life estimation: A review of the current status and future trends. *Nanotechnology and Precision Engineering*, 6, 2023.
- [22] Fernando Miguel De Sousa. *Fatigue assessment of old riveted railway bridges*. PhD thesis, FEUP, 2016.
- [23] Helder Pereira, Abilio De Jesus, Alfredo Ribeiro, and Antonio Fernandes. Fatigue damage behaviour of structural components under variable amplitude loading. *Revista Mecânica Experimental*, 17:75–85, 2009.
- [24] Zhi-Gang Xiao and Kentaro Yamada. A method of determining geometric stress for fatigue strength evaluation of steel welded joints. *International Journal of Fatigue*, 26:1277–1293, 2004.
- [25] Timothy Righiniotis, Boulent Imam, and Marios Chryssanthopoulos. Fatigue analysis of riveted railway bridge connections using the theory of critical distances. *Engineering Structures*, 30:2707–2715, 2008.
- [26] Ali Fatemi and Darrell F. Socie. A critical plane approach to multiaxial fatigue damage including out-of-phase loading. *Fatigue & Fracture of Engineering Materials & Structures*, 11:149–165, 1988.
- [27] H. Jakubczak and G. Glinka. Fatigue analysis of manufacturing defects in weldments. *International Journal of Fatigue*, 8:51–57, 1986.
- [28] Hanpin Lim and Stephen Hoag. Plasticizer effects on physical–mechanical properties of solvent cast soluplus® films. *AAPS PharmSciTech*, 14, 2013.
- [29] H. Neuber. Theory of stress concentration for shear-strained prismatical bodies with arbitrary nonlinear stress-strain law. *Journal of Applied Mechanics*, 28(4):544–550, 1961.
- [30] G. Glinka. Calculation of inelastic notch-tip strain-stress histories under cyclic loading. *Engineering Fracture Mechanics*, 22:839–854, 1985.
-

-
- [31] G. Glinka. Energy density approach to calculation of inelastic strain-stress near notches and cracks. *Engineering Fracture Mechanics*, 22:485–508, 1985.
- [32] Walter Ramberg and William R. Osgood. Description of stress-strain curves by three parameters. 1943.
- [33] G. R. Irwin. Analysis of stresses and strains near the end of a crack traversing a plate. *Journal of Applied Mechanics*, 24(3):361–364, 1957.
- [34] Xian Kui Zhu and James A. Joyce. Review of fracture toughness (g, k, j, ctod, ctoa) testing and standardization. *Engineering Fracture Mechanics*, 85:1–46, 2012.
- [35] A.A. Griffith. *The Phenomena of Rupture and Flow in Solids*. Philosophical transactions / Royal Society of London. 1920.
- [36] Materion Brush Inc. Stress intensity and fracture toughness. *Technical Tidbits*, 2014.
- [37] Fazil Erdogan and George C. Sih. On the crack extension in plates under plane loading and transverse shear. *Journal of Basic Engineering*, 85:519–525, 1963.
- [38] W.E.Anderson P.C.Paris, M.P.Gomez. A rational analytic theory of fatigue. 1961.
- [39] Nondestructive Evaluation Physics : Materials. Fracture toughness. Available at <https://www.nde-ed.org/Physics/Materials/Mechanical/FractureToughness.xhtml>, accessed at March 2023.
- [40] Hugo De Vasconcellos and Corrêa Patrício. Pontes ferroviárias metálicas existentes-caracterização dos materiais e avaliação da fadiga railway metallic bridges portfolio-material properties and fatigue assessment. 2018.
- [41] Boulent M. Imam and Timothy D. Righiniotis. Fatigue evaluation of riveted railway bridges through global and local analysis. *Journal of Constructional Steel Research*, 66:1411–1421, 2010.
- [42] Bertram Kühn. Assessment of existing steel structures - recommendations for estimation of the remaining fatigue life. volume 66, pages 3–11. Elsevier Ltd, 2013.
- [43] Q. Collette, I. Wouters, and L. Lauriks. Evolution of historical riveted connections: Joining typologies, installation techniques and calculation methods. volume 118, pages 295–306, 2011.
- [44] Björn Åkesson. Fatigue life of riveted railway bridges. 1994.
- [45] W.J. Lineham. *A Text-book of Mechanical Engineering*. Chapman & Hall, 1902.
- [46] M. D’Aniello, F. Portioli, L. Fiorino, and R. Landolfo. Experimental investigation on shear behaviour of riveted connections in steel structures. *Engineering Structures*, 33:516–531, 2011.
- [47] Abba G. Lichtenstein. The silver bridge collapse recounted. *Journal of Performance of Constructed Facilities*, 7:249–261, 1993.
- [48] Robert J. Dexter and Justin M. Ocel. Manual for repair and retrofit of fatigue cracks in steel bridges. 2013.
-

-
- [49] Enfant 490 L', S W Plaza, and D C Washington. National transportation safety board highway accident report, 2007. Available at = <http://www.nts.gov>.
 - [50] Robert C. Byrd Center for Congressional History and Education. The legacy of the silver bridge collapse. Blog, Year of publication. Available at = <https://www.byrdcenter.org/blog/the-legacy-of-the-silver-bridge-collapse>, accessed on April 2023.
 - [51] S Hao and M Asce. I-35w bridge collapse. *Journal of bridge engineering*, 2010.
 - [52] Liang Fang, Zhongqiu Fu, Bohai Ji, and Yuqiang Gao. Fatigue crack-propagation law of diaphragm-to-rib welded joint in steel bridge deck. *Journal of Constructional Steel Research*, 194:107311, 2022.
 - [53] A. Bassetti, P. Liechti, and A. Nussbaumer. Fatigue resistance and repairs of riveted bridge members. In G. Marquis and J. Solin, editors, *Fatigue Design and Reliability*, volume 23 of *European Structural Integrity Society*, pages 207–218. Elsevier, 1999.
 - [54] Vladimir S. Sokolinsky, Kyle C. Indermuehle, and Juan A. Hurtado. Numerical simulation of the crushing process of a corrugated composite plate. *Composites Part A: Applied Science and Manufacturing*, 42:1119–1126, 2011.
 - [55] Parvez Alam, Dimitrios Mamalis, Colin Robert, Christophe Floreani, and Conchur O'Bradaigh. The fatigue of carbon fibre reinforced plastics - a review. *Composites Part B: Engineering*, 166, 2019.
 - [56] H. Dong, Z. Li, J. Wang, and B. L. Karihaloo. A new fatigue failure theory for multidirectional fiber-reinforced composite laminates with arbitrary stacking sequence. *International Journal of Fatigue*, 87:294–300, 6 2016.
 - [57] Rui Guo, Chenggao Li, Yanzhao Niu, and Guijun Xian. The fatigue performances of carbon fiber reinforced polymer composites e a review. 2022. Available at = <https://doi.org/10.1016/j.jmrt.2022.11.053>.
 - [58] Yongzheng Shao, Kazuya Okubo, Toru Fujii, Ou Shibata, and Yukiko Fujita. Effect of matrix properties on the fatigue damage initiation and its growth in plain woven carbon fabric vinylester composites. *Composites Science and Technology*, 104:125–135, 2014.
 - [59] Trent C. Miller, Michael J. Chajes, Dennis R. Mertz, and Jason N. Hastings. Strengthening of a steel bridge girder using cfrp plates. *Journal of Bridge Engineering*, 6(6):514–522, 2001.
 - [60] Ardalan Hosseini, Elyas Ghafoori, Riadh Al-Mahaidi, Xiao Ling Zhao, and Masoud Motavalli. Strengthening of a 19th-century roadway metallic bridge using nonprestressed bonded and prestressed unbonded cfrp plates. *Construction and Building Materials*, 209:240–259, 6 2019.
 - [61] Yue Liu, Bernd Zwingmann, and Mike Schlaich. Carbon fiber reinforced polymer for cable structures-a review. *Polymers*, 7:2078–2099, 2015.
 - [62] Kelly. Anisotrop elasticity. *Solid Mechanics Part I*.
 - [63] F. Buiochi, M. A.B. Andrade, N. Perez, and J. C. Adamowski. Ultrasonic characterization of anisotropic materials. *Comprehensive Materials Processing*, 2:65–81, 1 2014.
-

-
- [64] Thimmappa Shetty Guruprasad, Vincent Keryvin, and Alain Bourmaud. Estimation of anisotropic elastic properties of carbon fibers using nanoindentation. *Acta Polytechnica CTU Proceedings*, 27:107–111, 2020.
- [65] Zhixin Zhan, Hu Weiping, Li Binkai, Zhang Yanjun, Meng Qingchun, and Guan Zhidong. Continuum damage mechanics combined with the extended finite element method for the total life prediction of a metallic component. *International Journal of Mechanical Sciences*, 124, 2017.
- [66] Paulo M.S. Tavares de Castro. Dimensionamento á fadiga. 2017.
- [67] Carlos Fernandes. Dimensionamento á fadiga: Fadiga orgãos de máquinas.
- [68] Murilo Augusto Vaz, Julio Cesar Ramalho Cyrino, and Gilson Gomes da Silva. Three-dimensional stress concentration factor in finite width plates with a circular hole. *World Journal of Mechanics*, 03:153–159, 2013.
- [69] A. Santos. Determination of stress concentration factors on flat plates of structural steel. *Journal of Physics Conference Series*, 466:2035–, 11 2013.
- [70] ANSYS. *ANSYS Academic Research, Release 17*. ANSYS, Inc., 2017.
- [71] Albertino Arteiro and Paulo Castro. *Mecânica da Fratura e Fadiga*. FEUP edições, 1^o edition, 10 2014.
- [72] Go Yamamoto, Shogo Kurisaki, Satoshi Atobe, and Tomonaga Okabe. Determination of full elastic constants of carbon fiber in carbon fiber reinforced plastic composites.
- [73] Prashob P S, A.P. Shashikala, and Thekke Somasundaran. Determination of orthotropic properties of carbon fiber reinforced polymer by tensile tests and matrix digestion. 2017.
- [74] Cláudio S. Horas, Abílio M.P. De Jesus, Diogo Ribeiro, and Rui Calçada. Efficient multiscale methodology for local stress analysis of metallic railway bridges based on modal superposition principles. *Engineering Failure Analysis*, 138, 2022.
- [75] Idilson A. Nhamage, Ngoc-Son Dang, Cláudio S. Horas, João Poças Martins, José A. Matos, and Rui Calçada. Performing fatigue state characterization in railway steel bridges using digital twin models. *Applied Sciences*, 13:6741, 2023.
- [76] Cláudio S. Horas, Abílio M.P. De Jesus, and Rui Calçada. New multiphase methodology for fatigue damage screening of aging metallic railway bridges. *International Journal of Fatigue*, 169, 2023.
- [77] C.S. Horas, A.M.P. Jesus, and R. Calçada. Integrated methodology for fatigue assessment of existing metallic railway bridges. volume 1, pages 1–7. Civil-Comp Press, 2023.
- [78] A. Fernández Canteli, E. Castillo, S. Blasón, J. A.F.O. Correia, and A. M.P. de Jesus. Generalization of the weibull probabilistic compatible model to assess fatigue data into three domains: Lcf, hcf and vhc. *International Journal of Fatigue*, 159:106771, 2022.
- [79] Wang Qiudong, Wang Libin, Ji Bohai, and Fu Zhongqiu. Modified effective notch stress method for fatigue evaluation of rib-deck welds integrating the critical distance approach. *Journal of Constructional Steel Research*, 196:107373, 2022.
-

-
- [80] Daoyun Yuan, Chuang Cui, Qinghua Zhang, Zongmou Li, and Zhongtao Ye. Fatigue damage evaluation of welded joints in steel bridge based on meso-damage mechanics. *International Journal of Fatigue*, 161:106898, 2022.
- [81] Donglin Jia, Qinghua Zhang, Lvbo Xiong, Jun Li, Yizhi Bu, and Yi Bao. A unified evaluation method for fatigue resistance of riveted joints based on structural stress approach. *International Journal of Fatigue*, 160:106871, 2022.
- [82] Cláudio S. Horas, José A.F.O. Correia, Abilio M.P. De Jesus, P. Kripakaran, and Rui Calçada. Application of the modal superposition technique combined with analytical elastoplastic approaches to assess the fatigue crack initiation on structural components. *Engineering Fracture Mechanics*, 185:271–283, 2017.
- [83] Horas Cláudio S., De Jesus De, and Calçada Rui. Efficient computational approach for fatigue assessment of riveted connections. *Journal of Constructional Steel Research*, 153:1–18, 2019.
- [84] Cláudio Horas, Abilio De Jesus, and Rui Calçada. Integrated methodology for fatigue assessment of existing metallic railway bridges. 2022.
- [85] En 1991-2: Eurocode 1: Actions on structures - part 2: Traffic loads on bridges, 1991.
- [86] Cláudio S. Horas, Abílio M.P. De Jesus, and Rui Calçada. Efficient progressive global-local fatigue assessment methodology for existing metallic railway bridges. *Journal of Constructional Steel Research*, 196:107431, 2022.
-