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CARBON FIBRE REINFORCED POLYMERS APPLIED IN STEEL STRUCTURES FOR IMPROVING FATIGUE BEHAVIOUR – A SHORT REVIEW

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Abstract: *Fatigue is a critical issue in structural engineering, characterized by the sudden and often catastrophic failure of elements subjected to cyclic loading, which can lead to significant material damage and loss of life. Carbon Fibre Reinforced Polymers (CFRP) composites is a promising alternative to traditional reinforcement methods, offering a direct, efficient, and cost-effective means to improve fatigue strength and repair damaged steel members. This paper provides a short literature review on the current advancements in the rehabilitation of steel structures, focusing on the application of CFRP for structural reinforcement. Key topics include the mechanical properties of steel and Fibre-Reinforced Polymer (FRP) composites, the bond characteristics between FRP and steel members, the fatigue performance of aged steel structures, and the current state of design codes and guidelines pertinent to FRP applications. Testing approaches from various research efforts are also examined in order to offer insights into current practices. The review highlights CFRP's economic and practical advantages, such as reduced costs for strengthening aging structures, shortened repair timelines, the ability to extend the lifespan of culturally and historically significant structures, and FRP's suitability for retrofitting steel structures due to its excellent strength-to-weight ratio and resistance to corrosion. The ease of on-site application and the low impact on traffic flow during repairs further enhance its appeal, especially for emergency repairs.*

Key words: *steel structures, fibre reinforced polymers, fatigue, reinforcement.*

1. Introduction

The failure of structural elements because of the fatigue phenomenon is extremely expensive, causing significant material damage, but more importantly, it can be catastrophic in terms of loss of human life. Since the failure of steel elements, affected by fatigue, is one that occurs suddenly, repairs are required immediately, in the shortest possible time. The

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phenomenon is mainly observed in structures subjected to repeated cyclic loads. In the construction field, some of the structures most affected by fatigue are road and railway bridges, the crane-supporting structures, cranes, sluice gates, and offshore platforms. Regarding the steel bridges, often they are classified as historical or of particular aesthetic or cultural importance. This makes dismantling and replacing of old structures with new ones to be the second option; on the contrary, rehabilitation and strengthening become the most suitable choice. Bridges, among all types of steel structures, due to their constant exposure to loads and environmental factors, are prime candidates for reinforcement using Fibre-Reinforced Polymer (FRP) composites.

Currently, more than half of the budget allocated by European authorities for infrastructure development is dedicated to maintenance and modernization, while less than half is allocated to expansion and renewal [30]. A study by European railway administrations covering nearly 220,000 bridges across Europe [9] showed that nearly 22% of bridges have steel structure. Of these, 28% of steel bridges are over 100 years old, and 40% are between 50 and 100 years old. Railway bridges are subjected to high stresses caused by extreme vibrations and dynamic deformations, which are increased by heavy traffic and the demand of high-speed trains.

Steel as a construction material was first introduced at the end of the 19th century, and gradually, as the industrial process advanced, more steel products became available. From the beginning, steel was used in the construction of various structures such as buildings, bridges, and industrial platforms. By the end of the 19th century, civil engineering experienced one of its greatest advancements, driven in part by scientific developments and modern static calculation methods. However, the field was not without its failures. Nonetheless, these failures often contributed to a better understanding of structural behaviour and to the development of new theories [30].

According to the study conducted by Oehme [34], out of a total of 448 reported damage cases, 98% occurred between 1955 and 1984, with 62% of these happening less than 30 years after construction. According to the data from this study, fatigue is a major cause of damage for various types of structures, and in the case of bridges, it ranks as the leading cause.

In the case of steel bridges, fatigue cracks are induced by secondary stresses, overloads, and incorrect assumptions regarding detail category during design, as well as poor workmanship (particularly in welding). Fatigue failures are rarely complete failures, as crack development leads to redistribution of stresses among other elements. This highlights the importance of redundancy when assessing fatigue safety. In elements with little or no redundancy, cracks propagate exponentially, starting slowly and accelerating. In contrast, in highly redundant elements, crack propagation occurs over a long period due to stress redistribution within the surrounding structural elements. Therefore, the end of life due to fatigue should not be considered solely when rupture occurs in the net section, but rather when an unacceptable difference is observed between the expected and actual structural behaviour [11], [12], [23], [30].

Most riveted bridges were built in the decades of the late 19th century and early 20th century. Therefore, they are over 100 years old and have passed their design life, which was not taken into account in their design. Many of these bridges have gone through various phases of repair or strengthening as a result of damage sustained in the two world wars or as a result of changing operational requirements. However, in many cases there is no visible fatigue damage. An important factor to consider is the economic aspect, which should not be overlooked. Decisions regarding consolidation or replacement with new structures must take into account both the current investment costs and the costs related to maintenance and preservation [31], [35]. Unlike riveted bridges, welded bridges have not yet reached their design life, the vast majority being built after 1950. However, considerable fatigue damage has been observed, either due to the limited knowledge of fatigue in welded structures at the time or because of the unforeseen increase in traffic [31].

The traditional methods most often applied to strengthen steel members affected by fatigue consist of steel plating, which includes welding and/or joints with added elements; drilling a hole at the tip of the crack; or crack welding. However, these methods have several drawbacks. The addition of new elements negatively impacts the structure by increasing the loads, altering the static scheme, or visually by raising the gauge. In order to strengthen damaged elements by attaching strengthening steel plates or elements, new holes or welding are required. For riveted structures, defective rivets must be replaced with pre-tensioned high-strength bolts, which may sometimes lead to unforeseen effects. Additionally, welding on older structures can be challenging or even impossible due to the poor weldability of the steels used at the time.

When drilling holes at the tip of the crack, in order to stop its propagation, it should be noted that accurately identifying the exact location of the crack's tip can be challenging and can easily be missed during repairs [25], [35].

Considering the aforementioned research results, traditional methods may prove ineffective both in terms of applicability and economic viability. On the other side, using CFRP composites to increase the fatigue strength of damaged steel members is a promising technique that provides an attractive alternative to traditional methods. In recent decades, the application of CFRP composites to strengthen structural elements has become an effective option to cope with increased cyclic loads or repairs caused by corrosion or fatigue cracks. CFRP composites offer a direct and efficient option, with numerous advantages, including their thinness and low weight, which reduce not only the visual impact but also the additional loads. Moreover, they offer the opportunity to do repairs without disrupting traffic, they can preserve aesthetic and historical values, and they are highly flexible, enabling them to take various shapes [35], [40].

2. Materials

A vital first step to applying the strengthening procedure is understanding the materials involved and how they work together. Both the existing materials and the strengthening materials need to be characterized [37].

2.1. Steel

The history of steel constructions is relatively short; it is thought to have started in 1778 when the footbridge at Coalbrookdale in England was built. There are three distinct stages: the cast iron, wrought iron, and mild steel (after 1900). In a first phase, all joints were made by riveting. Welding as a means of joining appeared at the beginning of the 20^{th} century. When dealing with structural rehabilitation, older structures are often encountered, constructed using materials specific to their era. Evaluating the properties of these materials can be challenging due to their age, unique composition, and the potential lack of historical documentation.

One of the biggest differences between assessing an old structure compared to a new one is that the information on structure and materials needs to be estimated. This information can be obtained from drawings and static calculations, measurements, material testing, non-destructive testing, and on-site inspections [31]. According to SIA 269/3 standard [36], the test methods shall be carried out in accordance with the EN 10025 [18] series of European Standards.

The most important material characteristics, according to Kühn et al. [31] are:

- chemical characteristic values (C, Si, Mn, P, S, N);
- yield strength: R_{eL} (lower yield stress of the material, often also called f_y), R_{eH} (upper yield stress of the material);
- tensile strength Rm (f_u);
- fracture toughness expressed in: K_{Mat} (material fracture toughness) (K_{Ic}), J_{Mat} (J_{Ic}, J_{crit}), ΔK (elastic stress intensity factor range), ΔK_{th} (threshold value of the elastic stress intensity factor range).

Old riveted steel structures from the 19^{th} century were made of wrought and mild steel. Wrought steel has a lamellar microstructure with a ferrite matrix and slag layers, while mild steel shows sulfuric segregation. The early 20^{th} century saw rapid steel development, but during periods like World War I, World War II, and the Great Depression, the steel quality lowered due to limited access to alloys and urgent demand.

The mechanical properties and chemical composition of old steel can vary significantly, depending on the manufacturer, year, and country of manufacture. The characteristic values shown in Table 1 may be used as the characteristic values of structural steel or cast iron [37].

Characteristic values of old structural steels and cast-iron [37] Table 1

Material	Period of use[1)]	f_{yk}[2)] [N/mm^2]	f_{uk}[2)] [N/mm^2]	G_k [GPa]	E_k[2)] [GPa]	ε_{uk}[2)] [%]	ν	ρ_a [kg/m^3]	α_T [10^{-6} / °C]
cast iron[3)]	before 1900	+70/-200[4)]	+120/-600	29	78	<0.8	0.26[5)]	7250	10
wrought iron	1850-1900	220	320	77	200	15	0.3	7800	10
mild rimmed iron	1890-1900	220	320	77	200	25	0.3	7800	10
	1900-1940	235	335	81	210	25	0.3	7800	
mild steel	1925-1955	235	360	81	210	25	0.3	7850	10

[1)] Main phase of manufacture;
[2)] Parallel to the direction of rolling;
[3)] Cast iron with lamellar graphite in accordance with EN 1561:1997;
[4)] Conventional value at 0.1% ultimate strain, since cast iron has no yield range;
[5)] Average value for different types of cast iron.

The steel toughness of old structural steel or cast iron shall be determined by means of Charpy V-notch bar impact tests in accordance with EN 10045-1 [19]. With the exception of cast iron and Thomas steel, old structural steels have a minimum Charpy V-notch impact value of K_V = 27J at a temperature of T_{27J} = 20°C.

Older structures typically feature riveted connections, with screws and welding used in more recent ones. When no other data is available, material properties can be determined through mechanical testing. Characteristic material properties for rivets are shown in Table 2.

Characteristic material properties for rivets [37] Table 2

Material	Period of use[1)]	f_{ukB} [N/mm^2]	ε_{ukB} [%]
wrought iron	1859-1900	320	18
mild rimmed iron	1890-1940	320	28
mild steel	from 1925	350	30
[1)] Main phase of manufacture.			

Without precise specifications and clear classification, bolts of an existing structure may be classified under the equivalent strength class 4.6.

Although 19th-century mild steel meets the requirements of EN 10025 [18] and may be classified as weldable based on their analysis, it is recommended that additional welding tests be conducted. For wrought steel and early mild steel, subjected to fatigue, steel should not be welded. The steels used since 1966, in welded structures, fully fulfil the general technical delivery conditions of the Eurocodes [31], [37].

2.2. Fibre-reinforced Polymer (FRP)

Fibre-reinforced polymers (FRPs) are composite materials consisting of two components: the polymer fibres that form the reinforcement and the adhesive used to bind the polymer fibres to the structure. The most used types of fibres are glass fibres, carbon fibres, or aramid fibres (aromatic polyamide); however, other types of fibres such as wood fibres, paper, or asbestos have also been used. This indicates that composite materials can either be engineered or naturally occurring materials.

The vast majority of FRP composite materials consist of rigid fibres with superior mechanical strengths in a matrix that is weaker and less rigid. The objective of this joining is to make a component that is strong and stiff, often with a low density. Commercial manufacturers typically opt to use glass or carbon fibres in matrices based on thermoset polymers such as epoxy resins or polyester. In certain cases, thermoplastic polymers are a preferred option because they are moldable after initial production. The recent increased interest in FRP materials has led to the development of more advanced forms of composites through the development of resins with superior performance or reinforcements such as nanotubes or nanoparticles [33].

FRP strengthening systems can be classified either from a morphological point of view or from a mechanical point of view [14, 15]. Morphologically, FRP systems can be divided into:

- pre-cured systems - are directly bonded to the structural strengthened element;

- wet lay-up systems - are impregnated with resin at the job site to the support;
- prepreg systems - are pre-impregnated at the manufacturing plant with partially polymerized resin.

From a mechanical perspective, FRP strengthening systems are classified based on their modulus of elasticity and ultimate capacity values. In Table 3 the main properties as a comparison between fibres, resin, and steel are presented.

Comparison between properties of fibres, resin, and steel (typical values) [14] Table 3

	Young's modulus E	Tensile strength σ_r	Strain at failure ε_r	Coefficient of thermal expansion α	Density ρ
	[GPa]	[MPa]	[%]	[10^{-6} °C^{-1}]	[g/cm^3]
E-glass	70 - 80	2000 - 3500	3.5 – 4.5	5 – 5.4	2.5 – 2.6
S-glass	85 - 90	3500 - 4800	4.5 – 5.5	1.6 – 2.9	2.46 – 2.49
Carbon (high modulus)	390 - 760	2400 - 3400	0.5 – 0.8	-1.45	1.85 – 1.9
Carbon (high strength)	240 - 280	4100 - 5100	1.6 – 1.73	-0.6 – 0.9	1.75
Aramid	62 - 180	3600 - 3800	1.9 – 5.5	-2	1.44 – 1.47
Polymeric matrix	2.7 - 3.6	40 - 82	1.4 – 5.2	30 - 54	1.10 – 1.25
Steel	206	250 - 400 (yield) 350 - 600 (failure)	20 - 30	10.4	7.8

Fibres are made of very thin, continuous filaments and based on this fact they can be divided into the following, most common types:

- Monofilament: basic filament with a diameter of about 10 µm.
- Tow: untwisted bundle of continuous filaments.
- Yarn: assemblage of twisted filaments and fibres formed into a continuous length that is suitable for use in weaving textile materials.
- Roving: a number of yarn or tows collected into a parallel bundle with little or no twist.

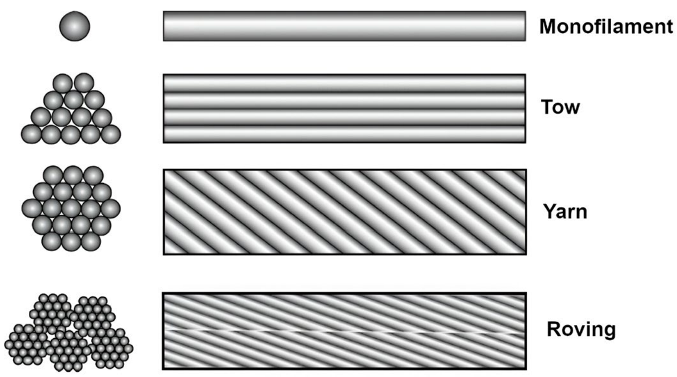

Fig. 1. *Types of fibres [14]*

In addition to yarns or rovings, fibres can also be found commercially in the form of fabrics. In this case, the arrangement of the fibres can provide quasi-isotropic properties of the fabric [14].

Glass fibres. Their most important characteristic is their high strength. Glass is mainly made of silicon with a tetrahedral structure (SiO_4). Some aluminium oxides and other metallic ions are then added in various proportions to either ease the working operations or modify the properties (e.g., S-glass fibres exhibit a higher tensile strength than E-glass).

Compared to carbon or aramid fibres, glass fibres have a lower modulus of elasticity and have relatively low abrasion resistance [14, 15, 33].

Carbon fibres. Carbon-Fibre-Reinforced polymers (CFRP) are high-strength polymer composites that contains carbon fibres with diameters of 9-17 μm, manufactured in a similar way to glass fibres.

According to [33, 40] carbon fibres can be classified based on several criteria, such as modulus of elasticity, strength and final heat treatment temperature.

Based on the properties of carbon fibres:

- High-modulus, type HM (modulus between 350-450 GPa);
- Intermediate-modulus, type IM (modulus between 200-350 GPa);
- Low modulus and high-tensile, type HT (modulus < 100 GPa, tensile strength > 3.0 GPa);
- Super high-tensile, type SHT (tensile strength > 4.5 GPa).

Based on precursor fibre materials, carbon fibres are classified into:

- Polyacrylonitrile-based (PAN) carbon fibres;
- Pitch-based carbon fibres (a viscoelastic material composed of aromatic hydrocarbons);
- Mesophase pitch-based carbon fibres (a mixture of high molecular weight molecules containing a small number of side groups);
- Isotropic pitch-based carbon fibres (carbon fibre made from isotropic pitch, which is a by-product of petroleum or coal tar refining);
- Rayon-based carbon fibres (semi-synthetic polymer made from cellulose);
- Gas-phase-grown carbon fibres (carbon fibres produced in an atmosphere of hydrocarbons with the help of fine particulate solid catalysts like iron or other transition metals).

Based on final heat treatment temperature, carbon fibres are classified into:

- Type-I, high-heat-treatment carbon fibres (HTT), where final heat treatment temperature should be above 2000°C and can be associated with high-modulus type fibre;
- Type-II, intermediate-heat-treatment carbon fibres (IHT), where final heat treatment temperature should be around or above 1500°C and can be associated with high-strength type fibre;
- Type-III, low-heat-treatment carbon fibres, where final heat treatment temperatures not greater than 1000°C. These are low modulus and low strength materials.

Aramid fibres. They are organic fibres made of aromatic polyamides in a highly oriented form. In terms of modulus of elasticity and strength values, aramid fibres are between glass and carbon fibres. They have a similar creep behaviour to that of glass fibres, although they have superior strength and fatigue behaviour [14], [15], [33].

Matrices. Thermoset resins are among the most widely used in the production of composites. When mixed with a suitable reagent, they polymerize to become a solid, glassy material.

Thermoset resins have numerous advantages. Among the most important advantages are low viscosity (which facilitates fibre impregnation), good adhesion, good resistance to chemical agents, absence of melting temperature. As for the most notable disadvantages, it can be mentioned that there is a limitation to a range of operating temperatures, poor toughness, and sensitivity to moisture. The most common thermosetting resin used in civil engineering is epoxy resin, but polyester or vinylester resins are also widely used [14], [15], [33].

Epoxy resins. The epoxy resins used in FRP reinforcement systems have very good moisture behaviour, high resistance to chemical agents, and very good adhesive properties. These properties make them ideal for applications in marine environments, aerospace, and industrial flooring. However, epoxies can be more expensive and have longer curing times, which can increase production costs.

The maximum temperature at which they can operate depends on the formulation and reticulation temperature. There are no significant restrictions regarding the minimum temperature [14], [15], [33].

Polyester resins. Compared to epoxy resins, polyester resins exhibit lower viscosity and faster curing kinetics. These characteristics contribute to their enhanced versatility in applications, although they often come at the cost of ultimate mechanical properties. While epoxies offer superior strength, durability, and chemical resistance, polyesters are frequently preferred for applications where processing time is critical and material cost is a significant factor.

Common polyester resins used in composites include isophthalic, orthophthalic, and bisphenolic types. Vinylester resins, which balance the performance of polyester and epoxy resins, are often used in high-temperature and chemically aggressive environments [14], [15], [33].

Adhesives. A critical step in FRP composite strengthening involves the selection of a suitable adhesive and surface treatment method. Proper substrate preparation, considering physical, chemical, and mechanical adhesion mechanisms, is essential for optimal bond performance.

The role of adhesives is to be able to create a bond between at least two surfaces and to be able to transmit loads between them. Several types of natural or synthetically obtained adhesives can be found, but the most suitable for use in composite materials are those based on epoxy resin. Adhesive bonding offers advantages over mechanical anchorage, such as joining dissimilar materials, enhancing stiffness, and avoiding stress concentrations [14], [15], [33].

3. Bound between FRP and metallic substrate

An essential aspect when conducting research in FRP composite application to strengthen fatigue-damaged steel elements, particularly involving experimental testing on specimens at both small and large scales, is a comprehensive understanding of the interaction and synergistic behaviour between the two materials. This aspect extends beyond merely understanding the intrinsic properties of the materials; it is equally critical to ensure that specimen preparation and testing methodologies are appropriately designed to achieve reliable and meaningful results. Furthermore, all potential failure modes that may arise during the exploitation of the structure must be taken into account.

Over the years, numerous researchers have investigated various methods of applying the FRP composites on different types of steel specimens. According to the authors of the paper [40], these methods can be classified as follows.

Type 1 – loading is indirectly applied to FRP composites (Figure 2) by means of a steel plate added to the tension flange of a beam.

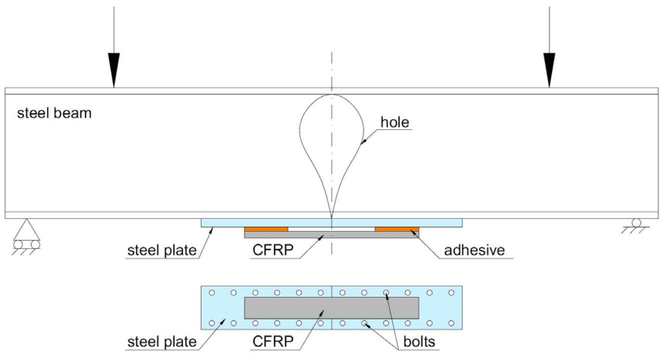

Fig. 2. *Type 1, load indirectly applied to FRP [40]*

Type 2 – loading is applied directly on the steel element without a gap. The load is transferred by the steel element to the FRP composites.

For this type, there are different ways of manufacturing the specimens, some of them are presented in Figures 3, 4 and 5.

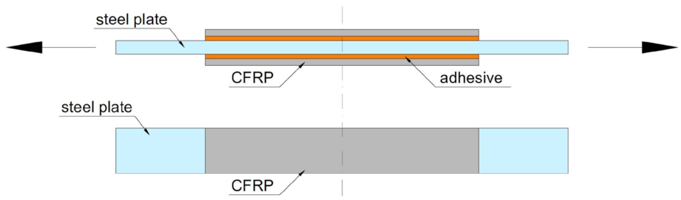

Fig. 3. *Type 2, load is directly applied to the steel element without any gap (uniform width specimen) [40]*

For specimens of uniform width, there is the possibility of yielding in the areas not covered by the composites. To eliminate this shortcoming, specimens with "coupon" or "dogbone" shapes were proposed. The specimens specific to the type 2 method are well-suited when testing for tensile stress.

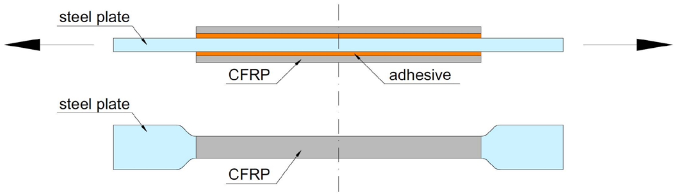

Fig. 4. *Type 2, load is directly applied to the steel element without any gap („coupon" shape specimen) [40]*

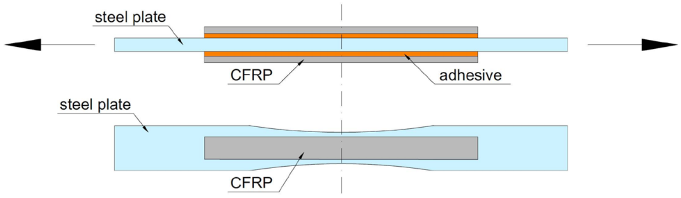

Fig. 5. *Type 2, load is directly applied to the steel element without any gap („dogbone" shape specimen)* [40]

Type 3 – loading is applied directly to the steel element with a gap between the joined steel elements. This test method is useful for studying the bond between the steel element and FRP strips. The main disadvantage of this method of application lies in the uncertainty of the location of the detachment at failure.

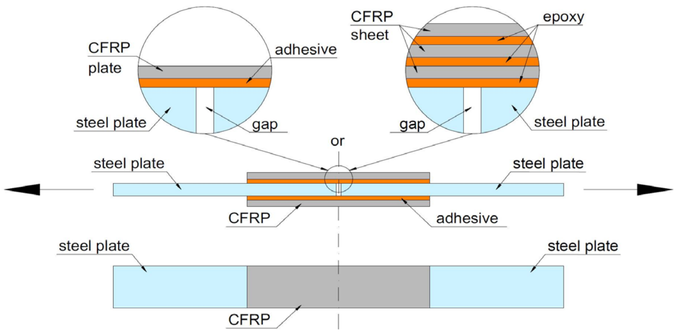

Fig. 6. *Type 3, load is directly applied to the steel element with a gap (double strap joints)* [40]

Type 4 – loading is directly applied to the FRP. Both tensile and compressive forces can be applied to composite plates. It should be noted that the FRP strips are generally utilized in tension; they do not possess a high enough resistance to compression.

By using this type of FRP application method, the bond between the steel element and the FRP composites can be studied.

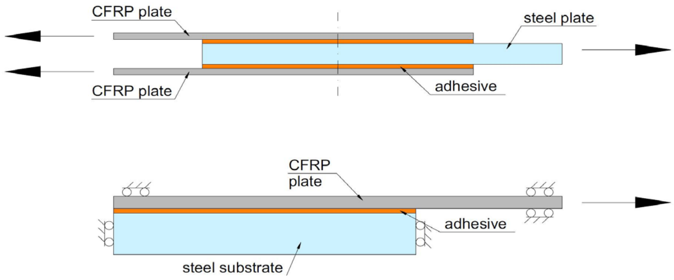

Fig. 7. *Type 4, Loading is directly applied to the FRP (double/single lap shear joint) [40]*

Experimental studies in the literature present various approaches to the application of FRP composites for strengthening steel elements or structures. These approaches include the application of FRP strips directly onto the affected steel elements without pretensioning, fixed with adhesives; the application of prestressed FRP strips affixed to steel elements with adhesives; and the use of pretensioned strips mechanically anchored to the metallic substrate through specialized clamping devices.

A very important step in assessing the behaviour of the bound between the FRP composites and the metallic substrate is to consider the possible modes of failure. For tension load, the following modes of failure can be considered (Figure 8) [40]:

- failure at the adhesive-metal interface;
- failure in the adhesive layer (cohesive failure);
- failure at the adhesive-reinforcement interface;
- CFRP delamination (detachment of some fibres from the resin matrix);
- rupture in CFRP;
- steel yielding.

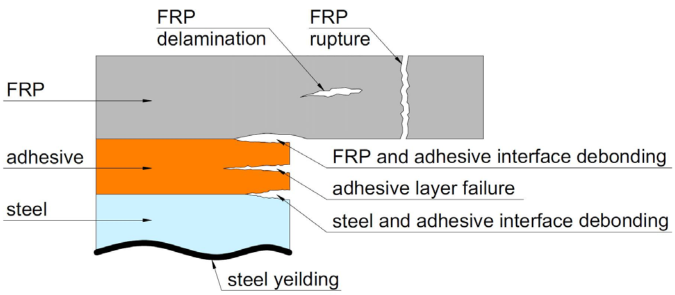

Fig. 8. *Typical failure modes (tension load) [40]*

Following research results presented in [22, 28, 39], it was found that the failure modes depend on the modulus of elasticity of the composites and the type of adhesive and its thickness. The cohesive failure tends to occur for thin adhesive, while the delamination failure mode occurs for thick adhesives. The failure at adhesive-metal or adhesive-reinforcement wasn’t observed, as for steel, yielding is often avoided in testing (by use of sufficient thickness).

4. Fatigue assessment of existing steel structures

Fatigue refers to the progressive damage and eventual failure of materials under cyclic loads in engineering applications, typically occurring at stress levels far below the material's ultimate strength. It results from repeated fluctuations between maximum and minimum stress. Final failure typically happens in areas of tensile stress when the reduced cross-section can no longer support the peak load without rupture. After repeated load cycles, accumulated damage leads to crack initiation and growth in plastically damaged regions, potentially causing component fracture [32].

According to Kühn et al. [31], the aim of fatigue assessment is to ensure the safety and functionality of an existing structure for a specific residual service life. The assessment process can be divided into four main phases.

Phase 1: Initial assessment. The aim is to remove all doubts about safety. This is achieved by using simple methods to identify the critical members of the analysed structure. The evaluation consists of gathering information about the analysed structure, performing design calculations according to present-day standards, and site visits.

Phase 2: Detailed investigations. It aims to update information and conduct a more refined assessment for the members that do not meet safety criteria. It is achieved through quantitative inspections, updated values of load and resistance, and more accurate design models.

Phase 3: Expert investigation. It is conducted for problems that have large implications in terms of risk and costs. It is achieved by a team of experts, who will analyse results obtained in phase 2 and propose the next steps in structure evaluation.

Phase 4: Remedial measures. Aims at proposing measures that conduct a safety fit for service structure. Different measures may be imposed: increased monitoring, reduced loads or change of destination, or strengthening/repairing the structure.

Following the general structural evaluation procedure, a specific assessment process for fatigue consisting of four phases can be formulated. These phases will be presented in more detail below, according to *Kühn et al.* [31].

4.1. Preliminary evaluation

The preliminary evaluation aims to remove uncertainties regarding safety by using simple methods and identifying critical members in the structure. It is important at this stage to gather information on the execution of the structure or how it has been maintained. In this phase, the evaluation can be conducted as in the case of a new structure, applying current design codes and recommendations. Most design codes are based on the classification method, which consists of determining the S-N curves in conjunction with the detail category. For the fatigue limit state, the safety level can be defined as:

$$\mu_{fat} = \frac{\Delta\sigma_c / \gamma_{Mf}}{\gamma_{Ff} \cdot \Delta\sigma_{E,2}} \tag{1}$$

where:

μ_{fat} - fatigue safety level;
γ_{Ff} - partial safety factor for equivalent constant amplitude stress range $\Delta\sigma_{E,2}$;
$\Delta\sigma_{E,2}$ - equivalent constant amplitude stress range at $2{\cdot}10^6$ cycles;
$\Delta\sigma_C$ - fatigue resistance at $2{\cdot}10^6$ cycles (detail category);
γ_{Ff} - partial safety factor for fatigue strength $\Delta\sigma_C$.

As a complementary method, the geometric stress method can be used. In this method, the value of the stress range is evaluated at the location of cracking by appropriate means.

4.2. Detailed investigation

It aims to deepen the calculations for the members found to be critical in the previous phase, for which the safety was considered to be unsatisfactory. The calculation is carried out in the form of a degradation accumulation calculation, the most frequently used method being the Palmgren-Miller linear method [28], [31], [32].

Because loads can be either superior or inferior to those considered in the design phase, the following steps are recommended.

Updating the load information. Instead of considering loads recommended by design codes it is recommended the use of actual measured loads and a more refined design model.

Refining the design model. In the preliminary phase the design model is in most cases conservative, thus the stresses obtained can be 10-40% larger compared to the real ones. This can have quite an impact on the fatigue life assessment.

Updating resistance information. Since the consideration of S-N characteristic curves for the determining of fatigue strength is usually conservative, it may lead to the adoption of resistances lower than the real ones.

4.3. Expert investigation

Fracture mechanics. Until this point, the fatigue resistance was assessed by means of the classification method. Although this method has certain advantages, like the ease of calculation, it still has a major drawback in that it cannot provide information regarding the size of cracks and cannot predict their propagation in different phases of the designed life of the structure. To counteract this shortcoming, the fracture mechanics method is used [2], [31]. This method can also be used to determine periodic inspection intervals. One of the limitations of fracture mechanics is the fact that its application to determine "distortion-induced" cracking due to secondary stresses is quite complex.

The basic principle in the formulation of the linear elastic fracture mechanics method consists in that only one parameter is necessary to describe the stress state very close to the crack tip, namely the stress intensity factor K. In general, it can be described by the following expression:

$$\Delta K = Y \cdot \Delta\sigma \cdot \sqrt{\pi \cdot a} \tag{2}$$

where:

a - crack size;

$\Delta\sigma$ - stress range;

Y - the product of various multipliers which account for the geometry of the crack, the geometry of the cracked body and (if necessary) the effect of non-uniform applied stresses.

Based on the stress intensity factor and by means of Paris law, the rate of crack propagation can be determined with the following relationship:

$$\frac{da}{dN} = C \cdot \Delta K^m \tag{3}$$

where:

C - constant of the Paris law;

m - exponent of the Paris law.

By integrating over crack size, the fatigue life of the detail can be obtained:

$$N = \int_{a_0}^{a_c} \frac{da}{C \cdot \Delta K^m} \tag{4}$$

where:

a_0 - initial crack size;

a_c - final or critical crack size.

Probabilistic methods. The variation of some parameters required for the design using either the classification method, geometric (hot-spot) stress method, or fracture mechanics can have a significant effect in determining the fatigue life. One of the methods used to take this aspect into account is the probabilistic method, which can be used together with the classification method or fracture mechanics. In the probabilistic method, input parameters that are treated as deterministic in the classification method or fracture mechanics are instead represented by statistical distributions. The probability of failure is then determined for a predefined limit state function. An important step in formulating the probabilistic model, whether based on the classification method or fracture mechanics, is defining this limit state function.

At the end of the evaluation in phase three, a report is prepared outlining the critical elements and the conclusions derived from the calculations.

4.4. Remedial measures

If all assessments up to this point cannot provide ample justification for using the structure in its current condition, then appropriate remedial action will be taken. Possible measures that can be taken consist of repairs, strengthening, intensive monitoring, reduction of loads and traffic volume, and, in the worst case, demolition of the structure.

5. Design codes and guidance

The use of polymer composites for strengthening reinforced concrete structures is a well-established practice. However, their application in strengthening steel structures is still relatively limited.

While for the design of steel structures, there are well-established and mature standards, the application of FRP composites for the strengthening of metal structures is still an emerging field.

Given the ongoing growth of the FRP composite materials market and the complexity of FRP-reinforced structures, it has become increasingly evident that standardization in this field is necessary. These standard documents must cover both the production of FRP structural systems and the practical rules for the design and verification of structures. However, there are some documents and design guidelines relevant to the application of FRP in the field of construction. Thus, in recent years, various documents from different countries have been published with the aim of serving as design guides, among which it may be appropriate to mention the following ones [3]:

- EUROCOMP Design Code and Handbook - Structural Design of Polymer Composites (1996) [13];
- CUR96 Fibre Reinforced Polymers in Civil Load Bearing Structures (2003) [16];
- CIRIA C595 Strengthening Metallic Structures Using Externally-Bonded FRP (2004) [38];
- BÜV Tragende Kunststoff Bauteile im Bauwesen - Richtlinie für Entwurf, Bemessung und Konstruktion (Load-bearing polymer components in construction - Guideline for design, dimensioning and construction) (2010) [10];
- BD90/05 Design of FRP Bridges and Highway Structures (2005) [8];
- CNR-DT 202/2005 Guidelines for the Design and Construction of Externally Bonded FRP Systems for Strengthening Existing Structures (2007) [15];
- ACMA Pre–Standard for Load and Resistance Factor Design of Pultruded Fibre Polymer Structures (2010) [1];
- DIN 13121 Structural Polymer Components for Building and Construction (2010) [17].

The Italian CNR-DT series of documents is among the most frequently referenced guides. These documents follow a structure similar to the Eurocodes. However, it is important to note that these documents are of an informative nature; they are not a mandatory regulation.

In addition to the documents aimed at providing recommendations for using composite materials in the reinforcement of steel structures, equally important are the guidelines concerning the inspection and intervention on existing structures. The Swiss series of guidelines, SIA 269 [37], outlines the fundamental principles and procedures for assessing existing structures.

5.1. General considerations on CIRIA C595 guideline

Stratford *et al.* [38] propose four main stages for carrying out an FRP composite strengthening project: consideration of the materials involved; design following a consolidation scheme; application of FRP reinforcement; and exploitation of the strengthened structure (Figure 9).

Fig. 9. *Stages for carrying out a FRP composite strengthening project [37]*

In the CIRIA report [37], the authors propose three stages for carrying out the design process of an FRP strengthening project, namely: conceptual design, detailed design, and structural analysis.

Conceptual design. The strengthening of a steel structure can be achieved in various ways, not solely by increasing its load-bearing capacity. Strengthening can also involve enhancing stiffness, increasing connection capacity, improving flexural tension and shear resistance, or reducing live load stress levels. Each of these objectives can contribute to extending the structure's fatigue life. Depending on the specific situation (whether the steel is brittle or ductile), decisions must be made regarding the appropriate strengthening solution - whether to use FRP with medium or high modulus or to apply FRP strips or plates.

Detailed design. After all the input parameters (existing structure, materials, design parameters, and environmental conditions) are determined, the quantity of the required strengthening material is determined. Where appropriate, the effects of dynamic loads and fatigue should also be examined.

Structural analysis. In this step, the minimum cross-sectional areas of the FRP reinforcement elements are determined. The strengthened elements must be capable of carrying the imposed loads while also accounting for temperature effects, particularly on the adhesive. In most cases, the failure mode is dominated by adhesive failure, making the evaluation of the bond between the adhesive and other elements a critical step. When determining the adhesive's strength, two approaches are recommended: an elastic, stress-based approach and a fracture mechanics-based approach, with the latter being considered the more definitive method.

Installation and operation. This document outlines guidelines for the installation of the reinforcement system and the operation of the newly reinforced structure. It stresses the importance of ensuring the system's functionality through high-quality installation, achieved by proper planning, the use of suitable equipment, adherence to environmental conditions, and the involvement of qualified and trained personnel.

The operational aspects are divided into two main categories: the inspection and maintenance of the strengthened structure and procurement and management issues, which will be of particular interest to the structure's owners. Once the reinforced structure is put into service, regular periodic inspections are required throughout the remaining lifespan of the structure. Any defects identified during these inspections should be addressed through appropriate repairs. Non-destructive testing (NDT) methods can be utilized as part of the inspection process; however, no single NDT method is likely to detect all potential defects. Furthermore, the currently available NDT methods for inspecting FRP-strengthened structures are still under development.

5.2. General considerations CNR-DT 202 guideline

The approach outlined in CNR-DT 202/2005 [15] closely follows that of the Eurocodes, with the primary aim of providing guidance on the design process, installation of the FRP strengthening solution, and the monitoring and maintenance of the reinforced structure. The following aspects are covered in detail: basis of strengthening and special issues; strengthening of tensile elements; flexural strengthening; debonding strength; strengthening of fatigue-sensitive elements; installation, monitoring, and maintenance.

The main objectives in the process of strengthening steel structures are as follows: enhancing or restoring *tensile strength*, improving or restoring *flexural strength*, and increasing *fatigue resistance*. The strengthening design should ensure tensile stress in the FRP, enabling it to function with the metal support. FRP use in compressive zones is not recommended due to insufficient models and tests on delamination. If the metal element is in an advanced state of corrosion, it must be completely removed before applying the composites. When strengthening fatigue-sensitive elements with FRP or using the prestressing technique, adhesive creep phenomena should be considered.

The CNR-DT Guide [15] proposes the use of partial safety coefficients in a manner similar to the Eurocode standards. The partial safety coefficients influence various aspects, including the FRP strengthening, adhesive/interface properties, and the resistance, durability, and behaviour of FRP composites.

For the metallic substrate, it is recommended to use the partial coefficients provided by the specific design norms.

The partial safety factors for FRP strengthening are influenced by the installation method and the quality of the application. The durability and behaviour of FRP composites are affected by the conversion factor: $\eta = \eta_a \cdot \eta_l$, where η_a is the environmental reduction factor and η_l is the reduction factor for long-term effects.

Strengthening of tensile elements. The failure mode of tensile elements strengthened by FRP materials can be associated with the failure of the metallic substrate, failure of the FRP reinforcement, or failure due to delamination.

For structural elements that are damaged but not due to fatigue, the restoration of load-bearing capacity is achieved by assuming that the stresses across the damaged section are bridged by the FRP reinforcement.

$$2 \cdot A_f \cdot \frac{f_{fk}}{\gamma_f} \cdot \eta \geq A_s \cdot f_{sk,sup} \tag{5}$$

where:

A_f - cross-section area of the FRP;

f_{fk} - lower characteristic value of the composite tensile strength;

γ_f - partial factor of the reinforcement material;

η - conversion factor;

A_s - cross-section area of the metallic substrate;

$f_{sk,sup}$ - upper characteristic value of the yielding stress (f_y) for ductile material, or failure stress (f_u) for brittle material.

In service condition, the stresses in the composite, evaluated with reference to the quasi-permanent load combination, must be:

$$\sigma_f \leq \eta \cdot f_{yk} \tag{6}$$

Flexural strengthening. The failure modes of beams strengthened by FRP composites can be associated with: tension failure of either the metallic beam (fracture or yielding depending upon the type of base material) or FRP; compression failure of the metallic beam (yielding or local buckling); delamination at the interface between the composite reinforcement and the metallic beam; shear failure by local buckling at the beam supports; or global buckling of the metallic beam. The design of the composite metal-FRP beam must thoroughly consider fatigue effects, as fatigue failure may occur not only in the metallic beam but also in the FRP reinforcement or the adhesive layer.

The ultimate limit state is verified by checking the following equation:

$$M_{Sd} \leq M_{Rd} \tag{7}$$

where:

M_{sd} - bending moment produced by the design load combination;

M_{Rd} - design value of the flexural capacity.

The ultimate limit state occurs when the strain at the extreme fibre of the cross-section reaches a limit value, determined by the previously outlined failure modes.

The stress-strain relationship of the metallic beam varies depending on the material, differing between ductile metals and brittle metals. For a *ductile steel*, according to EN 1993-1-1 [21], if the cross-section is class 1 or 2, failure will occur due to excessive strain in the FRP strengthening system. For a class 3 cross-section, failure may result from either yielding of the metallic beam or excessive strain in the FRP. In a class 4 cross-section, failure will occur due to local buckling of the compression flange or excessive strain in the FRP strengthening system. For a *brittle metal* (such as cast iron), the stress-strain relation is non-linear in tension and linear in compression. For a metallic beam made of a brittle material, all potential failure modes must be checked, as no pre-determined cross-section classification is available.

For the *serviceability check*, the metallic beam should be evaluated according to the design code of practice. The following limit must be respected for the FRP:

$$\left(\frac{\sigma}{f_{fk}}\right)^2 + \left(\frac{\tau}{\tau_{fk}}\right)^2 \leq \eta^2 \quad (8)$$

where:

σ, τ - the normal and shear stresses, respectively, acting at the generic point of the composite FRP strengthening system;

f_{fk} - characteristic value of the composite tensile strength;

τ_{fk} - characteristic value of the shear strength of the composite FRP strengthening system, measured in the direction perpendicular to the beam axis;

η - conversion factor.

Evaluation of the debounding strength. Delamination results from peeling and shear stress in the adhesive layer. Although delamination could theoretically occur in the metallic substrate, the typical resistance hierarchy is: adhesive joint, reinforcement, and substrate. Two approaches have been proposed to analyse the delamination: a conventional stress approach, based on the elastic analysis of the stress field, and a fracture mechanics approach, based on linear elastic fracture mechanics concepts.

The guide only deals with the stress-based approach. In a strengthened element with a metallic substrate, the potential delamination failure modes are as follows:

- delamination at the substrate - adhesive or adhesive - FRP interface;
- cohesive failure of the adhesive;
- delamination in the strengthening material.

The stress-based and fracture mechanics approaches use linear elastic relationships, making delamination checks valid only in elastic regions, such as the strengthening ends.

Strengthening of fatigue-sensitive elements. The failure modes considered in the strengthening of fatigue-sensitive elements are the fatigue delamination of the FRP reinforcement and the fatigue damage of the metallic substrate.

The ends of the FRP reinforcement and areas with discontinuities (cracks) are the most fatigue-sensitive zones of the adhesive joint due to stress concentration. No reliable model, like the S-N curve, exists for assessing the fatigue resistance of the adhesive joint. In the absence of experimental data, the fatigue limit can be approximated as 20–30% of the static failure strength.

Fatigue crack propagation in the metallic substrate is a function of the effective stress range ($\Delta\sigma_{eff}$). Based on the effective stress range, the effective stress intensity factor (ΔK_{eff}) is then determined. Crack propagation ceases when the effective stress intensity factor range falls below the corresponding threshold value ($\Delta K_{eff,th}$; γ_s - partial safety factor):

$$\Delta K_{eff} \leq \frac{\Delta K_{eff,th}}{\gamma_s} \quad (9)$$

Experimental evidence shows that fatigue cracks propagate only in the metallic substrate, not on the FRP material, causing partial delamination of the FRP strengthening. However, no reliable models are available to quantify this phenomenon. The design of a fatigue-damaged metallic structural element strengthened with FRP can be based on S-N curves or fracture mechanics principles.

6. Testing methods and research results

Concerning the assessment of structures subjected to repeated cyclic loading, numerous studies conducted over the years have introduced various testing methodologies. Among the most common testing methods found in the literature are tests conducted on small-scale specimens made from steel recovered from old dismounted structures or of modern steel with similar properties. Additionally, for comparative purposes, specimens made of modern steel, are also tested. The tests performed on large-scale were, in the majority of cases, carried out on elements (assemblies), which were part of old, now dismounted structures. A notable drawback of this approach, besides others, is the requirement for specialized equipment capable of performing such tests, which is often not readily accessible. Additionally, the size of the tested elements (assemblies) presents a significant drawback. In addition to small-scale and large-scale testing methods, researchers sometimes adopt the intermediate-scale testing; by choosing this approach, the aim is to reduce or eliminate the disadvantages associated with large-scale testing methods.

In the following, a concise overview of the studies conducted by various researchers on the application of FRP composites for the strengthening of steel structures affected by fatigue will be presented.

Jones *et al.* [25] conducted an experimental and analytical study to highlight the effectiveness of applying CFRP polymer composites to steel members affected by fatigue. The tests were performed on a series of specimens made with a notch or with a central hole subjected to cyclic, repeated axial loading. The main variables considered during testing were bond length, bond area, application of the composites on one side or on two sides, and application before or after crack propagation. The specimens (Figure 10), were made according to the American ASTM E-338-97 standard [5], and then they were subjected to a uniaxial loading cycle at a constant amplitude of 25 Hz and a maximum load of 37.8 kN.

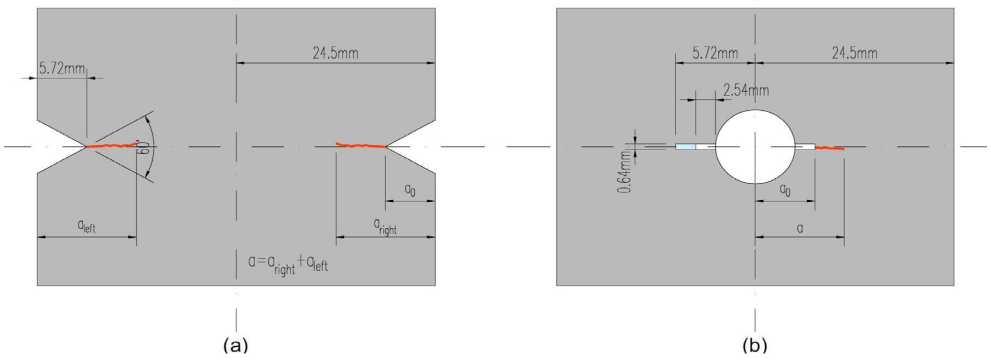

Fig. 10. *Plate Scheme of specimens. (a)notch specimen (b) hole specimen. [35]*

The test results showed that the application of CFRP overlays can extend the fatigue life of the specimens. The authors first pointed that adhesive behaviour had a critical role in the effectiveness of the strengthening system and that CFRP composites with moderate elastic modulus had the best behaviour. All failures had as their starting point the debonding of the CFRP; by contrast, the rupture of the fibres never occurred. Regarding the application on one side or on both sides, it was found that the application on one side increases the fatigue life only slightly compared to unstrengthen specimens. The possible explanation is that in the case of axial load, the application on one side produces bending in the element. The behaviour of the specimens with CFRP plastered on both sides was superior. Another benefit mentioned in this paper is the application of CFRP strips over defects (cracks), in which case the CFRP strips showed their highest efficiency. In conclusion, according to the tests performed, the fatigue life was extended between 115-170% depending on the method of application. The authors mentioned as a possible increase of the strengthening efficiency the application of prestressed CFRP.

Hassan *et al.* [26] experimentally investigated the behaviour of steel plates that have different levels of deterioration for different reinforcement schemes. The authors tried to reproduce experimentally the effects of other loads, not only axial forces, thus showing other ways of crack surface displacement (Figure 11).

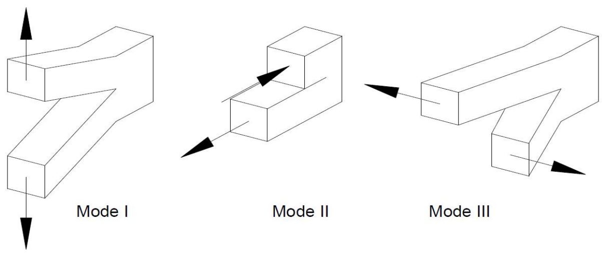

Fig. 11. *Modes of crack surface displacement [26]*

The specimens were made in accordance with the American ASTM E647-13 [6] standard. Three groups were considered according to the level of deterioration, namely 22%, 30%, and 40%. The specimens were reinforced by three types of CFRP laminate applications: laminates applied to the entire height of the specimen on both sides; laminates applied to the entire height of the specimen on a single side; and laminates applied to half of the height of the specimen on a single side. The specimens were subjected to an eccentric loading cycle with a frequency of 20 Hz specific to steel bridge loading. The test results showed that the predominant mode of failure for the control specimens was rupture in the steel plate, as a result of the propagation of the crack in the weakened steel section. For the reinforced specimens, the failure occurred in the adhesive-steel interface, followed by the debonding of the CFRP laminates. The conclusions of the test showed that applying CFRP reinforcements reduces the propagation of fatigue cracks, thus increasing the fatigue life, but this depends on the chosen scheme. The specimens with the level of deterioration of 22% had an increase of fatigue life between 7% and 49%; those with the level of damage of 30% had an increase of fatigue life of 23%; and those with the level of deterioration of 40% had an increase of fatigue life between 33% and 127%. Also, the arrangement of the laminates on both sides and the longer length had a positive impact on the strengthening solution.

In their study, Kasper *et al.* [29] conducted a series of experimental tests to demonstrate the benefits of toughened epoxy in comparison to untoughened epoxy. The main difference between classic, untoughened epoxy and toughened epoxy adhesive is the introduction of a flexible phase into the stiff epoxy matrix. This flexible microstructure increases toughness through mechanisms like void growth, shear banding, and rubber-bridging. These mechanisms enhance energy dissipation during crack growth, resulting in higher fracture energy.

In order to determine the mechanical parameters, several experimental tests were conducted. First, tensile and compression strength tests were carried out in order to determine the resistance to tensile and compression loading and the value of the modulus of elasticity. Tensile strength tests were conducted according to ISO527-2 [27] specifications, while for compression tests, measurements were performed according to ASTM D695 [4]. For assessing the ability to maintain adhesion when force is applied parallel to the bond line, lap shear strength tests were performed according to DIN EN1465 [20]. Impact wedge-peel resistance and dynamic mechanical thermos analysis were also performed. In order to assess the deformation behaviour of the adhesives under permanent loading, creep tests were carried out.

Fatigue tests were conducted to investigate the potential of CFRP application reinforcement to fatigue-damaged steel components. For this purpose, centrically notched steel plates were reinforced with CFRP lamellas, and the residual life was determined experimentally. The test procedure was carried out in three phases. In the first phase, an initial crack was introduced into the specimen during the fatigue test. Then on phase two, the cracked steel sheet was reinforced on one or both sides with two 20mm-wide slack or pre-stressed CFRP lamellas on each side of the sheet. Finally, in the third test phase, the reinforced test specimen was subjected to a further fatigue test. The fatigue tests were carried out until the complete fracture of the steel sheet cross-section.

Finally, the effectiveness of reinforcement for fatigue-loaded steel components was investigated on a full-scale component. The test was conducted on a hollow profile made of S355 steel that was loaded in a four-point bending test (Figure 12).

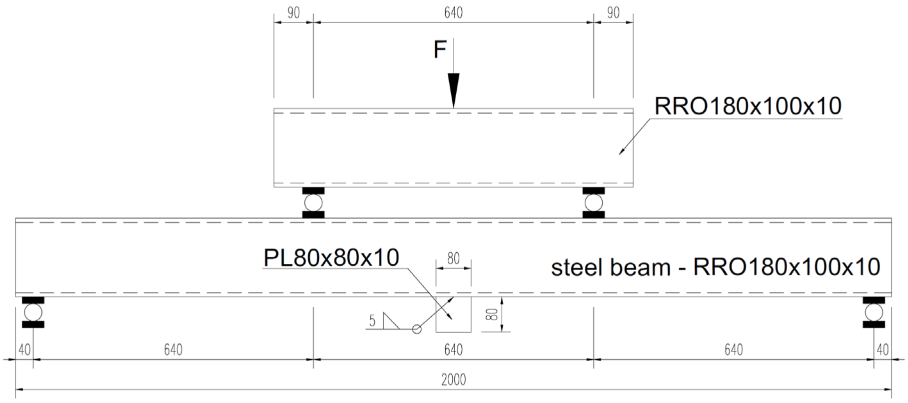

Fig. 12. *Test setup (large component test, dimensions in mm) [34]*

In the middle of the hollow section beam, a fin plate made of S355 was welded onto the wall. The specimen was subjected to a cycle load until a 40 mm long crack at the weld seam on one end of the fin plate transversely to the longitudinal axis of the component occurred.

In the next phase, the tensile stressed chord of the fatigue-damaged test specimen was reinforced with two pretensioned CFRP lamellas and then subjected to the same cyclic loading.

The results of all tests unequivocally highlighted the superior performance of toughened epoxy adhesives when compared to the untoughened ones. The prestressing of CFRP lamellas makes creep resistance crucial for the bonded joint. Creep tests indicate that the expected deformations are minimal. Fatigue tests on centre-notched steel specimens with toughened EP adhesive and CFRP lamellas show significant potential to reduce crack tip stress and extend service life. Reinforcing both sides with pre-stressed plates can increase the remaining service life by up to 7.9 times compared to unreinforced specimens.

Kowal and Pietras [30] notched specimens (Figure 13) made of puddled steel, obtained after the decommissioning of a railway bridge over 100 years old, and of S235JR steel were tested for comparison.

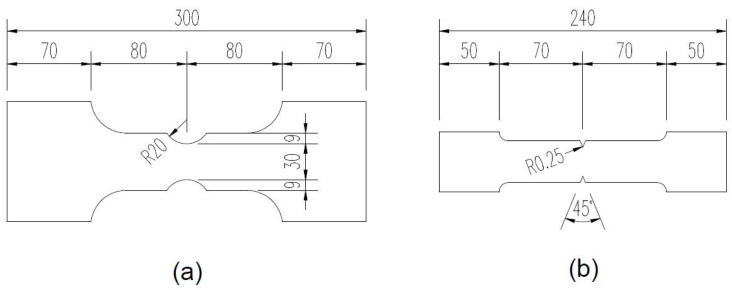

Fig. 13. *Scheme of specimens. (a) S235 mild steel; (b) old steel (puddle steel) [30]*

Strips of unpretensioned CFRP composites were applied to one side of the specimens. The specimens were fatigue tested, and the results showed a considerable improvement in fatigue behaviour for the CFRP-reinforced specimens. For CFRP-reinforced S235 steel specimens, the fatigue life increased by 2 to 16 times, and for old steel specimens, the fatigue life increased by 11 to 34 times. The authors of these studies mention among the advantages of CFRP strengthening the speed and ease of in-situ application of the composites, which offers a wide range of possibilities in case of the need for repair in an emergency situation. As for shortcomings, the authors emphasized, first of all, the meteorological conditions, which are quite strict during the application and also during operation, and the effect of temperature changes that have a negative effect on the adhesive (especially at temperatures below 0°C).

Tavakkolizadeh *et al*. [38] studied the behaviour of notched beams retrofitted with CFRP polymers, subjected to a medium cycle of repeated loading. The test method used by the authors was the four-point bending test; the loads were applied with frequencies between 5 and 10 Hz. Constant stress ranges with values between 69 and 379 MPa were considered. In order to create a fatigue-sensitive detail, the tension flanges of the beams were notched on each side (Figure 14).

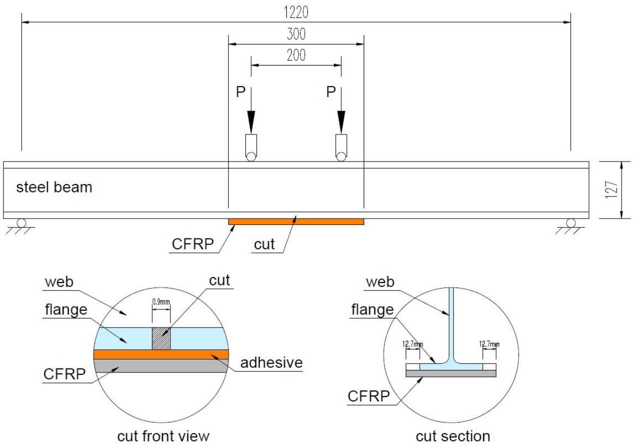

Fig. 14. *Schematic of loading setup [38]*

Over these areas (those containing the defects), CFRP strips, identical in length with medium strengths (2137 MPa) and low modulus (144 GPa) were attached. The beams used in the testing were cut at lengths of 1.3 m. In addition to the reinforced CFRP beams, unretrofitted beams were also tested for comparison. As for the unretrofitted beams, the vast majority failed at a number of cycles below $1.2 \cdot 10^6$, for stress ranges between 60 and 138 MPa. Test results showed better fatigue behaviour than calculated, leading to the idea (as stated by authors) that small-scale testing overestimates fatigue strength. The tests for the reinforced beams were carried out for higher ranges of stresses, but even so, a higher fatigue behaviour was obtained compared to what was obtained by calculation. A possible explanation for this result could be the reduced scale of the specimens. The results of fatigue life extension tests on CFRP-reinforced beams were very promising. Also, the effect on stopping/slowing down the propagation of fatigue cracks is notable. The fatigue life of reinforced beams was reported to be 2.6-3.4 times higher compared to unretrofitted beams. At the same time, the number of cycles to failure after crack initiation was 3.5 times higher in the case of reinforced specimens.

Bassetti *et al*. [7] presented another approach, consisting of the prestressing of CFRP composites fixed with adhesives on the reinforced steel element. The aim of the experiment was to remedy and arrest new crack development caused by fatigue concerning riveted elements that are part of steel bridge structures. The application of CFRP composite strips over the cracked steel section (perpendicular to the crack opening) reduces the stress range ($\Delta\sigma$) and also the crack opening to a certain extent. Finally, the stress field around the crack is modified by the effect of prestressing, which leads to the reduction or even stopping of crack propagation. The tests were carried out on small-scale specimens consisting of metal plates with a central hole (Figure 15) reinforced with CFRP strips, but also on large-scale where a riveted beam dismantled from a bridge over 90 years old (Figure 16) was tested.

The results of this study showed that the use of CFRP composites for the strengthening of old riveted steel bridges is an effective option resulting in the reduction or even stopping of fatigue crack propagation. An increase in fatigue life by a factor of up to 20 has been shown in small-scale test specimens. Large-scale tests on the riveted beam showed the possibility of producing significant compressive stresses by prestressing the composites directly on the metal elements.

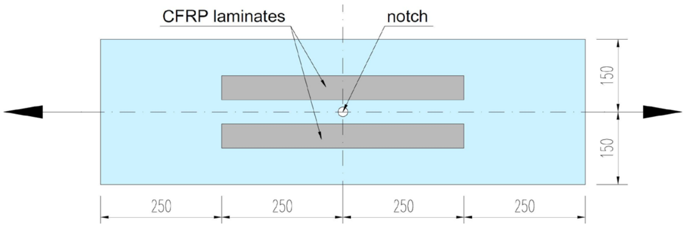

Fig. 15. *Specimens [7]*

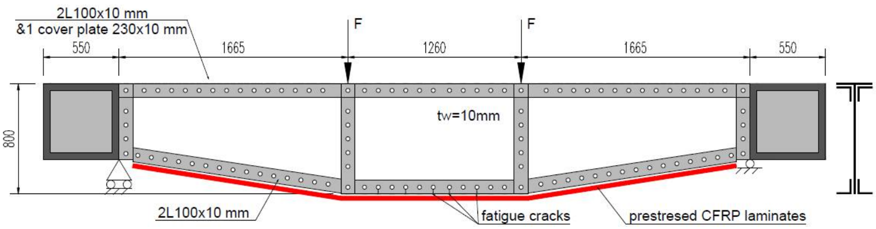

Fig. 16*. Load application on the cross-girders and location of fatigue cracks [7]*

In all previous papers, the authors opted for the common approach of fixing the FRP reinforcement with adhesives on the metal structure. In the work [24], *Ghafoori et al.* chose a different approach for strengthening a riveted steel railway bridge over 100 years old, still in use. In this paper, it is proposed to achieve the strengthening using pre-tensioned CFRP strips attached externally to the structural element (Figure 17) by using clamps and other devices.

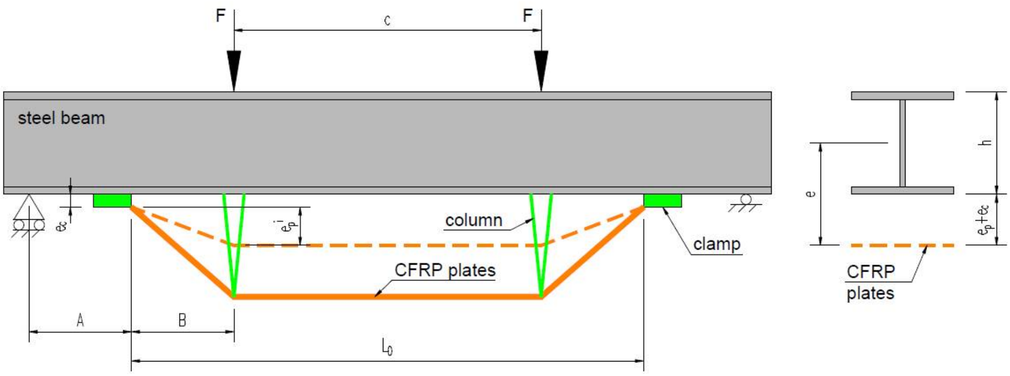

Fig. 17. *Load application on the cross-girders and location of fatigue cracks [24]*

The results of this study showed that the application of a prestressing force for a fatigue-sensitive structure can reduce the level of mean stresses so that it moves from the finite fatigue life regime to the infinite fatigue life regime. The method used has a great advantage, especially if the stress history is not known or cannot be determined easily. Unlike the usual methods, this method does not require the preparation of the reinforced steel element surfaces (the devices are fixed directly on the reinforced element). At the same time, this method also solves other problems related to the usual application of composites, such as the influence of temperature and humidity or the fatigue loads that occur at the bond of the adhesive with the steel element. It also eliminates the difficulty of attaching composites to riveted or corroded surfaces, which can be an inconvenience in many cases.

6. Conclusions

This paper presents a concise literature review on the application of Carbon Fibre Reinforced Polymers (CFRP) as structural reinforcement. It examines the properties of metal substrates and fibre-reinforced polymer (FRP) composites as well as the bond between FRP and strengthened steel members. Additionally, the manuscript highlights current research on fatigue assessment, design codes, and guidelines specific to FRP application, as well as it summarizes various studies conducted by researchers in this domain in the past years. Among the most significant conclusions regarding the benefits of applying FRP composites are their economic advantages, the reduced time required for repair work, and their potential to extend the lifespan of historically significant structures.

The costs associated with strengthening old structures could be, many times, lower than the costs of building new ones. Even more significantly, many of the old structures serve as historical landmarks and aesthetically pleasing monuments. Among other advantages worth mentioning are the short period required for repairs compared to the longer periods required to build a new bridge (or structure) or the fact that reinforcement can often be done without disrupting the traffic. In case of the need for repair in an emergency situation the speed and ease of in-situ application of the composites offer a wide range of possibilities.

CFRP materials exhibit a superior strength-to-weight ratio and excellent corrosion resistance compared to traditional methods, making them a compelling choice for strengthening old steel structures.

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