Fatigue Behaviour of Steel Bridge Joints Strengthened with FRP Laminates

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Abstract

One of the most relevant concerns about steel and metal bridges stands on the repair and rehabilitation of existing structures. In fact, the remaining service life of steel bridges is limited by fatigue damage and in order to ensure the safety of these bridges it is often necessary to inspect the structure in order to discover the presence of fatigue cracks. New reinforcement techniques are needed, in order to prevent fatigue cracking and to increase bridge safety at the same time. According to the contemporary knowledge on the matter, two alternatives of rehabilitation are given: the traditional interventions and the use of carbon fibre composites. In this paper, in order to explain the appropriate use of these techniques, the most common knowledge on the matter are presented and explained, focusing in particular on the real scale testing results coming from the last decades research applications related to steel bridge engineering. This study should in this way be useful for future research applications and for bridge engineering real case rehabilitations.

Keywords: fatigue, steel, bridge, rehabilitation, FRP

1. Introduction

The remaining service life of steel bridges is limited by fatigue damage and in order to ensure the safety of these bridges it is often necessary to inspect the structure in order to preclude the presence of fatigue cracks. Damage due to cyclic loadings deals with a fatigue failure that proceeds by gradual enlargement of fatigue cracks during the tensile part of the loading cycle; once a crack reaches a certain critical size, catastrophic failure ensues. The process of fatigue crack growth is evidenced by the formation of characteristic striation patterns on the fracture surface called beach markings, which are followed by the more irregular pattern characteristic of fast fracture. In order to maintain these bridges in service new reinforcement techniques are needed, in order to prevent fatigue cracking and increase bridge safety at the same time. The use of carbon fiber composites (CFRP) for structural reinforcements has shown increasing promise. Aside from the very high tensile resistance, composite materials have also demonstrated a very high fatigue resistance, which makes them particularly appropriate for the reinforcement of steel structures subjected to fatigue loads. Degradation of steel structures, such as old industrial buildings and bridges, and increased load requirements have led to the need for structural rehabilitation and strengthening. Another rehabilitation procedure stands on traditional applications as HS-bolting or welded steel plates to the original structure, sometimes used as a strengthening technique: some negative aspects such as the increase in permanent loads, difficulty of applications, and problems due to corrosion and fatigue have been demonstrated to affect also the new members or connections. On the contrary, fiber reinforced polymer (FRP) materials have a high strength-weight ratio, do not give rise to problems due to corrosion, are extremely manageable and are commonly used for strengthening structural existing members (Lua et al., 2005; Yuana et al., 2004; Jao et al., 2005; Pellegrino et al., 2002), but they have only been infrequently studied and used for strengthening steel elements and, above all, steel-concrete composite elements. Several studies on the FRP strengthening of concrete structures have resulted in the first design guidelines for concrete structures strengthened with externally applied FRP. American ACI 440-02 (ACI, 2002), European fib bulletin 14 (FIRB, 2001) and Italian Recommendations (CNR, 2004) are examples of such guidelines. Although externally bonded FRP strengthening for metal structures is a rapidly developing technique (Cadei et al., 2004), guidelines for the reinforcement of steel structures with FRP do not currently have a comparable degree of reliability. Some examples of guidelines for the design and construction of externally bonded FRP systems for strengthening...
existing metal structures are the ICE design and practice guide (Moj, 2001), CIRIA Design Guide (CIRIA Design Guide), US Design Guide (Schnerch et al., 2007) and document CNR-DT 202/2005 (CNR, 2005), which can currently be considered as a preliminary study. The benefits of composite strengthening are shown in some significant case studies like the successful strengthening of a steel bridge on the London Underground (Moj, 2007). The benefits of strengthening large cast-iron struts with Carbon FRP composites in the London Underground are illustrated in (Moj, 2006). Significant work in this area of research was also developed by (Tavakkolizadeh et al., 2003a; Tavakkolizadeh et al., 2003b; Shaat et al., 2006; Shaat & Fam, 2004; Sen et al., 1995; Miller et al., 2001). A state-of-the-art review on FRP strengthened steel structures was recently developed by Zhao and Zheng (2007). Main approaches proposed in the literature to study the phenomenon of delamination (Buyukozturk et al., 2004) are based on linear elastic analysis of internal stresses (Taljsten, 1997) and linear elastic fracture mechanics (Lenwari, 2005; Lenwari et al., 2006; Colombi, 2006). Other significant approaches to the determination of stresses in the adhesive layer are described in the CIRIA Design Guide (Cadei et al., 2004) and in the work of Deng et al. (2004). The fundamental work about stresses at the interface was reported in Smith and Teng (2001) and in Stratford and Cadei (2006). These theories have not been validated with a sufficient number of experimental results, due to the few experimental data available in the literature. One of the first studies on the flexural behaviour of steel beams reinforced with carbon-fibre reinforced polymer composites is that of Moy and Nikoukar (2002). Very recent works about strengthening steel structures using FRP are those of Schnerch and Rizkalla (2008) and Rizkalla et al. (2008). Current design guide lines propose a method to predict the flexural behaviour of FRP strengthened elements based on classic equilibrium and strain compatibility, usually within the elastic range of the materials. FRP laminate is always considered only under the tensile flange current in-depth information about the non-linear behaviour of FRP strengthened steel-concrete composite elements is scanty. Concerning the phenomenon of fatigue in existing steel bridge member, some works could be noticed in literature, dealing in particular with the assessment of riveted connections, both by full scale tests, or by step level procedure, or finally applied on real case applications (Pipinato et al., 2012a; Pipinato et al., 2012b; Pipinato et al., 2012c; Pipinato et al., 2012d; Pipinato et al., 2011a; Pellegrino et al., 2011; Pipinato, 2011; Pipinato et al., 2011b; Pipinato et al., 2010; Pipinato & Modena, 2010; Pipinato, 2010; Pipinato et al., 2009; Pipinato et al., 2008). This paper deals with the analysis of experimental tests developed in a variety of steel joints repaired with FRP laminates. The purpose of the study is to investigate three main groups of test: (a) tension tests on single plates with FRP reinforcement; (b) tension test on double plates with FRP reinforcement; (c) bending tests on reinforced full scale beams with FRP reinforcements on the lower flange. SN curves are provided in order to check the correspondence of experimental results and coded provisions.

2. Existing Metal Members

Iron bridges have been built since the industrialisation time period, which was the end of the 19th century, so old metal bridges could imply to assess a structure with an average age of more than 100 years. Several bridges even exist since the mid of the nineteenth century, leading to an age of more than 150 years. The early metal bridges in the 19th century were fabricated with cast iron or puddle iron (wrought iron). The manufacturing of puddle iron started in the beginning of the 19th century. Since it had a lower carbon content than cast iron, going along with a better ductility, it allowed forging and an easier workmanship. Yet towards the end of the 19th century puddle iron was superseded by mild steel that obtained higher qualities concerning the chemical analysis and cleanness of the steels as well as better technological material properties (e.g. weldability, strength). The steel production and construction technology (bolting and welding of joints) developed quickly but testing methods to examine relevant properties as toughness, fatigue, corrosion etc., were missing completely. Such testing methods were developed much later in the 20th century and related to modern steels rather than old steels of existing structures. Therefore only fragmentary knowledge exists concerning iron materials of the early times, complicating the handling and assessment of old metal structures. Already at the beginning of the 20th century metal bridges were built mainly with mild steel. It should be also considered that before 1910, there was little standardization in the industry: each steel producer used his own recipe and rules. This resulted in a wide variety of metals used, regarding the chemical and mechanical properties. Railway authorities, for instance, adopted specific rules only from 1900 in order to specify the materials to be used for iron railway bridges. In order to assess existing bridges it is essential to know the material properties and their characteristics. Constitutive materials could be: grey cast iron, wrought iron, mild steel and the contemporary steel product. Grey cast iron takes its name from the colour of the fracture face, has a carbon content of 1.5-4.3% and 0.3-5% silicon plus manganese, sulphur and phosphorus. It is brittle with low tensile strength, but is easy to cast. The characteristics of the material are good in compression but poor in tension. Thus, the structural parts where often designed to be in compression as arches, columns etc. The graphite flakes caused a significant brittleness of the material. Internal cracks could easily occur and propagate along the flakes when the iron was subjected to tensile stresses,
giving poor ductility properties. This material has a good wear resistance and damping abilities, absorbing vibrations and noise, even if it is brittle and has demonstrated a poor resistance to impact and shock. Cast iron is not suitable for welding due to its high carbon contents, which can lead to brittle cracks in and around welded joints. Wrought iron (or puddle steel) was the first structural steel until it was replaced by (mild) steel, in the end of the 19th century. It has a low carbon content, an high amounts of phosphor and nitrogen making the material brittle and escalating the ageing process. The microstructure is non homogenous due to the manufacturing process producing inclusions of sulphides and oxides. This led to anisotropy of the material which is especially bad in the thickness direction due to the arrangement of the inclusions and the influence of the rolling. As a matter of fact, the mass production of steel started with the Bessemer process 1856, followed by the Martin-Siemens process 1867 and the Thomas-Gilchrist process 1878. Most of the old metal bridges still used today consisted of steel produced with one of these processes. Production of steel in the end of the 19th and the beginning of the 20th century were conducted with a technique called chill module casting. The chill module casting was performed by pouring the steel from the oven in to a chill module to cool down before rolling of the steel. The cooling process in the module started from the borders, with high temperatures in the middle. During the cooling process almost pure steel formed at the borders and unwanted alloys and impurities increases towards the centre of the melt (depending on thermal properties). This manufacturing process lead to the formation of impurities and blisters increased in the middle of the steel, and for this principle reason steel produced during these circumstances are not considered appropriate as construction steel today. Moreover, an high concentrations of unwanted compounds formed in the middle of the steel that drastically lower the quality, so laminates manufactured with this technique are characterized by steel with very good qualities at the surface while the centre of the plate will be steel with brittle properties. At the same time, they are not suitable for welding, due to a differentiated toughness, and for this reason cracks can originate due to the residual stresses from the heat affected zone of the weld. Finally, contemporary steel materials, are coded and produced according to general standards and methodologies, for e.g. in Europe according to EN 1993-1-1 (2005), characterized by different material properties as the tensile resistance, the fracture toughness, the ductility requirements.

3. FRP Materials

The principal fibres that are used in FRP plate bonding to metallic structures are carbon fibres, aramid fibres and E-glass fibres: a summary of the indicative fibre properties is given in Table 1. Carbon fibre is characterized by excellent fatigue resistance, and do not suffer from stress rupture compared with glass or aramid fibres. Carbon fibre properties depend on the structure of the carbon used, so typically they come defined as standard, intermediate and high modulus fibres, depending from their structural behaviour. Aramid fibres have the highest strength to weight ratio (for e.g. Kevlar) and is characterized by similar tensile strength to glass fibre, but can have modulus greater at least two times; it could allow significant energy absorption but, compared to carbon, it is lower in compressive strength and has poorer adhesion to the matrix, finally it is also susceptible to moisture absorption. E-glass accounts for the larger part of the glass fibre use and is used mainly in a polyester matrix: the ‘E’ in E-glass stands for ‘electrical’ and was intended to indicate that the material has low electrical conductivity. It is commonly the the cheapest glass fibre and is therefore the preferred material in the construction market. Two types are available one contains boron, the other boron free: the corrosion resistance of E-glass without boron is approximately seven times the corrosion resistance of the boron-containing E-glasses.

4. Experimental Tests

The first group of experimental tests investigated, is represented by FRP reinforced steel plates under tension forces (Figure 1) (Jones & Civjan, 2003). Examined details were notched (N) or hole (H) provided: N11 not reinforced; N21 is made of 4 Sika Wrapex 103C resin on one side; N31 is made of Sika Wrapex 103C resin on two sides, L=255 mm; N41 is made as N31 but with a smoothed resin layer; N35 is made as N31 but with an unbalanced resin mix; N51 is made as N31 but with L=380 mm; N22 is made as N21 but with MBRACE CF130; N36 is made as N31 is made as N21 but with MBRACE CF130; H11 is not reinforced; H21-22 is made of Sika Wraplex 103 C on two sides, L=255 mm; H41-42 as H21 but with Sika Carbodur. In this test the FRP application caused eccentricity causing bars curvature, and as a result the performance doesn’t grow up if compared to the unreinforced test. Three types of CFRP have been used with diverse elasticity module, and varying thickness: from these tests it could be obtained that the best performance is obtained by using the CFRP with a lower E module (e.g. Sika WrapHex 103C). Moreover, from the obtained comparison on SN curves, an extended life has been obtained for: holed specimens, accurate preparation of the base layer, longer CFRP laminates. Category details, even if approximate, stands in the range C=140-160 for notched specimens, and on C=160 for holed specimens. A similar experimental testing has been provided as reported in Figure 2 (Monfared et al., 2008): in this test, similar specimens of the aforementioned test has been used. Variable parameters have
been used, as: a reinforcement on one or two sides, and the result was that a single side specimen has a longer fatigue life; an accurate sanded surface preparation, belonging to the result that the surface preparation doesn’t provide significant improvements. While in the reinforced specimens the failure stands on the reinforcement, in the not-sanded specimens the CFRP delaminates. In Figure 2 it could be noticed a tendency line for the failure specimens, belonging to the following detail category: C=78 for not-reinforced specimens, and C=82 for reinforced specimens. Another similar application has been developed (Zheng & Lu, 2006) and reported in Figure 3: in this study the reinforced detail on both sides highlighted a longer fatigue life, which is improved also by higher stiffness value, depending on the E module and on the thickness. The detail failed for delamination. The following detail categories were obtained: C=63 for not-reinforced specimens, and C=102 for reinforced specimens. The second group of experimental investigations analyzed, is represented by double strap FRP reinforced steel plates under tension forces (Figure 4) in this case the failure mechanism is represented by delamination for SDS specimens, and CFRP failure for the DDS, beyond the C=40 (Matta & Karbhari, 2005); in the second case (Liu et al., 2005), the failure mechanism is influenced by the CFRP module; with a normal module CFRP delamination prevail, while with higher module CFRP the composite laminates fails. Other studies, presents some analysis on existing bridge steel members specimens of the first of ‘900, taken out of service and repaired with CFRP: in the first cases (Bassetti, 2001) the CFRP stiffness is varying from SikaCarboDur S512 with a lower module (E=155 GPa) and laminates of 1.2 mm thick, to higher module (E=210 GPa) and laminates of 1.4 mm thick; the mechanical strength resulted to be not influenced from the quality of the resin, while the pre-tension of the CFRP could grow-up to 20 times the fatigue life; failure resulted to remain in the delamination of the CFRP. Other observations has been done in (Täljsten et al., 2001) in relation to the propagation speed growth of the CFRP, which has been demonstrated to depend from the pretension force, from the stress reversals and pre-tension, and from the importance of the cleaningness of the surface; as a result, pre-tensioned specimens could stop the crack propagation into the very high cycle phase: for e.g. a pre-tension specimen has been tested up to 16x106 cycles, belonging to an extended life raising eight times the category detail life. Moreover, the crack propagation has been observed to be symmetric except if a delamination raise up. In the graph reported in Figure 6 two groups has been presented: in red not-reinforced details, in blue reinforced details, with the further specifications denoted in the legenda. From these comparisons, it could be noticed some SN tendencies, such as C=100 for virgin specimens, C=106 for not reinforced beams, and C=152 for reinforced beams. The third group of experimental investigations analyzed, is represented by bending tests on steel beam (Figure 7): four riveted beams have been tested by bending fatigue tests. Reinforcing technique are for e.g. represented by cover-plating or rivet/bolt substitution or by stop-holes: the limits observed in the testing results are that these are applicable for small cracks, and could be applied in the first propagation phase; moreover, these technique are limited to local repairing. CFRP interventions are otherwise reported in the following Figure 8, in which not reinforced and a corresponding CFRP reinforced section has been tested; in particular for the Q4 specimen, it should be observed that the test has been stopped at 20 milion of cycles without failures nor crack propagation, while in the Q5 and Q8 specimens, even if large crack openings has been found before testing, these has been limited in the growing phase, and no CFRP reinforcement has been found at the end of the test. To sum up all the tests analyzed, the principles data have been reported in Tables 2 and 3.

Table 1. Typical fiber properties used in structural interventions

| Property                          | Ultra-high-modulus carbon fiber | High strength carbon fiber | High-modulus carbon fiber | Aramid fiber Kevlar 49 | E-glass fibre |
|-----------------------------------|---------------------------------|---------------------------|----------------------------|------------------------|--------------|
| Specific weight                   | 2.12                            | 1.80                      | 1.80                       | 45                     | 2.56         |
| Modulus of elasticity (GPa)       | 620-935                         | 230                       | 390                        | 130                    | 70           |
| Tensile strength (MPa)            | 3600-3700                       | 3400                      | 2900                       | 3000                   | -            |
| Strain to failure (%)             | 0.6                             | 1.48                      | 0.74                       | 2.3                    | -            |
| Coefficient of thermal expansion (10^-6 °C) | -                              | -1.0 to +0.4             | -1.0 to +0.4               | -5.2                   | 4.9          |
Figure 1. Fatigue failures of FRP reinforced steel plates subjected to tension forces

Figure 2. Fatigue failures and curve of FRP reinforced steel plates subjected to tension forces
| Reference | Campaign | Type of test | Dimensions | Ceramic mixtures | Detachment | A (Mpa) | n | New role nature | Inverse examples/notes |
|-----------|----------|--------------|------------|-----------------|------------|--------|---|-----------------|------------------------|
| Tirekkelzaad (2003) | Steel beams, Almstixed on flanges and reinforced with CFRP on the lower side at the mid span | Bending test | 512mm x 51, 2.2m long, CFRP 360N/mm², Ø 12mm | Far-364 Mpa, 109.5 Mpa, E=1042 Gpa, CFRP E=236 Gpa, steel stress = 212 Mpa | Beams reinforced at the lower flange at midspan | 207 | 246 | 276 | 345 | 1.184, 148 | 31,219, 37, 219 | 30,056, 25,988 |
| (Song 2007) | Steel beams: CFRP reinforced on the lower flanges at midpoint | Bending test | Steel beams: 512x512, 2.2m long, FRP 3.2mm thick, 488 mm long | Steel E=205 Gpa, steel yield 16.5 Normal, E = 8 Gpa, Y = 25.7 Mpa | Beams reinforced at the lower flange at midspan | 39 | 30 | 77 | 20,000 | 120,000 | 1.060,000 | The crack propagates from the end of the adherend to the steel-adhesive interface, with an angle of 40°. |
| Bassetti (1999) | Variable section steel members beams reinforced with traditional techniques | Bending test | Beam: 570x60mm long, angle profiles: 30x30x6.5x6.5mm, plate: 29x60x200mm | Steel beams: 521 Mpa, σy = 412 Mpa, σy = 312 Mpa. | G7T one plate; moment required | 80 | 72 | 92 | 97 | 100,000 | 12,178,000 | 25,668,000 | 13,000,000 | 5,144,000 | In these beams, the failure stands everywhere in the member. In case of short cracks, propagation could be stopped replacing the beam with FRP plates. |
| Bassetti (2001) | Variable section steel members beams not reinforced | Bending test | Beam: 570x60mm long, angle profiles: 30x30x6.5x6.5mm, plate: 29x60x200mm | Steel beams: 521 Mpa, σy = 412 Mpa, σy = 312 Mpa. | G7T one plate; moment required | 80 | 72 | 92 | 97 | 100,000 | 12,178,000 | 25,668,000 | 13,000,000 | 5,144,000 | In these beams, the failure stands everywhere in the member. In case of short cracks, propagation could be stopped replacing the beam with FRP plates. |
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Table 3. Tensile test on single steel plates, FRP reinforced

| Reference | Specimens | Test type | Dimensions | Materials | Details | Failure Notes |
|-----------|-----------|-----------|------------|-----------|---------|---------------|
| 1 (Baccarini, 2009) | S275 specimens reinforced on both sides with Sika carbothem NG4 | Tensile test | Steel specimens: 1000 mm long, 60 mm wide, 8 mm thick. FRP specimens: 40 mm long, 25.4 mm wide, 1.5 mm thick. | Steel S235: E = 210 GPa, nominal strength: 430 MPa, nominal tension strength: 480 MPa. | FRP: SikaCarbothem NG4. | N = 83, 85, 100, 140. | 5.800, 5.800, 5.800, 6.300 GPa. Failure mechanism started with the detachment from the edge of the specimen and then propagated on the whole element interface. A visual inspection revealed that the adhesion-steel interface is the weakest point of the system. |
| 2 (Hwang, 2001) | Single lap shear cleat plates | Tensile test | Steel specimens: 1000 mm long, 12.7 mm wide, 1.5 mm thick. FRP: normal thickness 0.22 mm. | Steel specimens: 1000 mm long, 12.7 mm wide, 1.5 mm thick. | Steel specimens: 1000 mm long, 12.7 mm wide, 1.5 mm thick. | N = 100, 100, 140, 140. | 34.362, 34.362, 41.586, 41.586 GPa. The most common failure mechanism has been found to be the detachment of the FRP from the steel plate. |
| 3 (James, J. A.) | 5 steel plates not reinforced and 5 steel plates reinforced on one or both sides | Tensile test | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | N = 305, 305, 165, 165, 165. | 375.418, 375.418, 232.191, 232.191, 232.191 GPa. Tensile failure occurs near the lap shear cleat for all tests, no failure has been observed in the fibres, fatigue cracks propagate beyond the CFRP strips. |
| 4 (Marsden, 2000) | 15 steel plates with holes and with FRP (on both sides), sanded or not | Tensile test | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | N = 165, 165, 165, 165, 165. | 200.651, 200.651, 200.651, 200.651, 200.651 GPa. Failure lies on the FRP for reinforced specimens, not on sanded specimens. |
| 5 (Neng, 1996) | 6 steel specimens strengthened at the centre, with 2 notches on either side, reinforced with CFRP on one or both sides. | Tensile test | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | N = 130, 130, 130, 130, 130, 130. | 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000 GPa. The tensile failure life is not related low-life results for reinforced specimens. The propagation speed of cracks in reinforced specimens on both sides is lower than that of one side reinforcement. The strength is higher with CFRP of high modulus and reinforced on both sides. |
| 6 (Kovacevic, 2001) | Steel specimens reinforced at the centre with cracks, representing fracture holes, reinforced with 2 CFRP strips past tensioned on both sides. | Tensile test | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 900 mm long, 25.4 mm wide, 1.5 mm thick. | N = 100, 100, 100, 100, 100, 100. | 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000 GPa. A detachment on the interface adhesive and steel has been observed and the adhesion failure strength has been determined to grow up the shear deformation at the adhesive layer. |
| 7 (Tanaka, 2000) | 5 metal specimens strengthened provided with no initial cracks | Tensile test | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | N = 100, 100, 100, 100, 100, 100. | 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000, 1,832,000 GPa. The detachment lies on the interface steel-CFRP. |

| Material | Component | Type of test | Dimensions | Characteristics | Details | N | Notes or remarks | Image notation [example] |
|----------|-----------|--------------|-------------|----------------|---------|---|----------------|---------------------|
| 8 (Matsuo, 2009) | Steel frame, angle joint (30°) or double angle joint (60°), strengthened with FRP on both sides. | Tensile test | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | N = 83, 83, 83, 83, 83, 83 | 1,800,000, 1,800,000, 1,800,000, 1,800,000, 1,800,000, 1,800,000 GPa. Proven combinations with categories of details are: H14 + SF6 CE 106 d. All combinations tested withstanding F-C24 test for all sides. The ultimate strength is not affected and is 1 cm distance between the delamination. Failure to exceed the composition. |
| 9 (Ito, 2000) | 12 plates joined at the centre reinforced with CFRP on both sides, metal and high modulus | Tensile test | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | Steel specimens: 950 mm long, 25.4 mm wide, 1.5 mm thick. | N = 90, 73, 73, 73, 73, 73 | 1,800,000, 1,800,000, 1,800,000, 1,800,000, 1,800,000, 1,800,000 GPa. Failure in the form of detachment in the interface FRP-H14 base. |
Figure 3. Fatigue failures and curve of FRP reinforced steel plates subjected to tension forces

Figure 4. Fatigue failures of double strap FRP reinforced steel plates subjected to tension forces
Figure 5. Fatigue failures of existing plates with FRP reinforcement subjected to tension forces

Figure 6. Fatigue failures and curves of different tests
Figure 7. Fatigue failures of steel beam with traditional techniques subjected to bending

Figure 8. Fatigue failures of steel beam with CFRP reinforcing subjected to bending
5. Conclusions

This study deals with the analysis and comprehension of the fatigue behaviour of steel bridge joint, reinforced with FRP materials. The actual state of art of FRP strengthening is presented and discussed in the first part of this paper, while in the second part experimental tests coming from literature are presented and analyzed. It should be noted that, although a sufficient number of experimental tests have been found in literature, FRP reinforcing experimentations are more frequent for reinforced concrete than for steel structures, because up to now steel engineering have privileged steel to steel interventions rather than FRP rehabilitations. The use of FRP offers advantages compared to traditional techniques, because the FRP has a high strength / weight ratio, higher than that of steel; moreover they are very resistant against corrosion, if not entirely free from this, and extremely manageable. However, they are not sufficiently resistant to fire: FRP loses its strength and stiffness properties with temperature and the degradation in FRP properties is faster as compared to concrete or steel since the properties of the FRP matrix start to deteriorate even at modest temperature; also, bond degradation is another concern with externally bonded FRP. The analysis of experimental research found in the literature for the fatigue behavior of FRP reinforced steel detailing has proven the effectiveness of the composite material to extend the fatigue life of steel structures and decrease the growth of cracks. Two main types of fatigue testing has been analyzed, tensile and bending tests. Moreover a distinction has been made for test on individual steel plates reinforced with FRP, test on two samples of steel combined with FRP on both sides and the third is the tests on beams reinforced with FRP at the bottom. Failures data and their correlation were obtained from experimental data and compared to SN curves. Details reinforced with FRP belong to categories higher than those mentioned in EC3: in fact, for e.g., the graph of the fatigue curves of small-scale details of specimens reinforced virgin belong to the category 102, the notched specimens at 75, drilled to test 109, the old metal reinforced with 90 and those pre-tensioned to 125. From this analysis were then derived for the design of appropriate observations. The results obtained have shown a generally better fatigue behavior of steel reinforced detail than non-reinforced. Concerning the categories of Eurocode 3-1-9, reinforced details improved the ductility of the joint and demonstrated an higher life if compared to those of welded details, and it was also noted that the fatigue life of the steel specimens that have drilled holes is extended if compared to that of steel specimens which have cracks. This could be confirmed by an analysis of linear elastic fracture mechanics: the propagation of a crack can be described by a law of Paris as known, which takes into account the amplitudes of the effective stress intensity factors, which confirms that the speed of propagation of the crack will be higher and the fatigue life minor. The type of failure in almost all cases appears to be the detachment of the CFRP from the steel surface, without damaging the composite. This demonstrates the high capacity of resistance of fiber-reinforced composite and the weakest point of the system is the interface adhesive/steel. Finally it was found that the failure modes depend on the modulus of elasticity of the CFRP, the type of adhesive and the thickness of the adhesive.

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References

ACI Committee 440. (2002). Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures (ACI 440.2R-02). American Concrete Institute, Farmington Hills, MI, USA.

Bassetti, A. (2001). Lamelles Precontraintes en Fibres Carbone pour le Renforcement de Ponts Rivet es Endomma ees par Fatigue (in French), Ph.D. Thesis no. 2440. Swiss Federal Institute of Technology, EPFL, Lausanne, 2001.

Bocciarelli, M., Colombi, P., Fava, G., & Poggi, C. (2009). Fatigue performance of tensile steel members strengthened with CFRP plates. Composite Structures, 87(2009), 334-343. http://dx.doi.org/10.1016/j.compstruct.2008.02.004

Buyukozturk, O., Gunes, O., & Karaca, E. (2004). Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites. Construction and Build Mater, 18, 9-19. http://dx.doi.org/10.1016/S0950-0618(03)00094-1

Cadei, J. M. C., Stratford, T. J., Hollaway, L. C., & Duckett, W. G. (2004). Strengthening metallic structures using externally bonded fibre-reinforced polymers. Design Guide, London, ISBN 0-86017-595-2.

CNR Italian Advisory Committee on Technical Recommendations for Construction. (2004). Guide for the design and construction of externally bonded FRP systems for strengthening existing structures. Materials, RC and PC structures.
CNR Italian Research Council, Italian Advisory Committee on Technical Recommendations for Construction. (2005). Guidelines for the design and construction of externally bonded FRP systems for strengthening existing structures. Preliminary study. Metallic structures (CNR-DT 202/2005). Italian Research Council, Rome, Italy; Masonry structures (CNR-DT 200/2004). Italian Research Council, Rome, Italy.

Colombi, P. (2006). Reinforcement delamination of metallic beams strengthened by FRP strips: fracture mechanics based approach. Eng. Fract. Mech., 73, 1980-1996. http://dx.doi.org/10.1016/j.engfracmech.2006.03.011

Deng, J., Lee, M. M. K., & Moy, S. S. J. (2004). Stress analysis of steel beams reinforced with bonded CFRP plate. Composite Struct. 65(2), 205-215. http://dx.doi.org/10.1016/j.compstruct.2003.10.017

EN 1993-1-1. (2005). Design of steel structures, Part 1-1: General rules and rules for buildings. CEN, European committee for standardization, Bruxelles, Belgium.

Fib Task Group 9.3. (2001). Externally bonded FRP reinforcement for RC structures. fib bulletin 14, Lausanne, Switzerland.

Jao, Y., Teng, J. G., & Chen, J. F. (2005). Experimental study on FRP-to-concrete bonded joints. Composites part B: Engineering, 36(2), 99-113. http://dx.doi.org/10.1016/j.compositesb.2004.06.001

Jones, S. C., & Civjan, S. A. (2003). Application of fibre reinforced polymer overlays to extend steel fatigue life. Journal of Composites for Construction, ASCE7(4), 331-338. http://dx.doi.org/10.1061/(ASCE)1090-0268(2003)7:4(331)

Lenwari, A., Thepchatri, T., & Albrecht, P. (2005). Flexural response of steel beams strengthened with partial-length CFRP plates. J. Compos Construct, 9(4), 296-303. http://dx.doi.org/10.1061/(ASCE)1090-0268(2005)9:4(296)

Lenwari, A., Thepchatri, T., & Albrecht, P. (2006). Debonding strength of steel beams strengthened with CFRP strips. J. Compos. Constr. 10(1), 69-78. http://dx.doi.org/10.1061/(ASCE)1090-0268(2006)10:1(69)

Liu, H. B., Zhao, X. L., & Al-Mahaidi, R. (2005). The effect of fatigue loading on bond strength of CFRP bonded steel plate joints. International symposium on bond. Proceedings of the International Symposium on Bond Behaviour of FRP in Structures (BBFS 2005).

Lua, X. Z., Teng, J. G., Yea, L. P., & Jiang, J. J. (2005). Bond-slip models for FRP sheets/platesbonded to concrete. Engineering Structures, 27(6), 920-937. http://dx.doi.org/10.1016/j.engstruct.2005.01.014

Matta, F., & Karbhari, V. M. (2005). Tensile response of steel/CFRP adhesive bonds for the rehabilitation of civil structures. Struct. Eng. Mech., 20(5), 589-608.

Miller, T. C., Chajes, M. J., Mertz, D. R., & Hastings, J. N. (2001). Strengthening of a steel bridge girder using CFRP plates. J. Bridge Eng., 6(6), 514-522. http://dx.doi.org/10.1061/(ASCE)1084-0702(2001)6:6(514)

Monfared, A., Soudki, K., & Walbridge, S. (2008). CFRP reinforcing to extend the fatigue lives of steel structures. Fourth International Conference on FRP Composites in Civil Engineering (CICE2008) 22-24, July 2008, Zurich, Switzerland.

Moy, S. S. J. (2001). FRP composites: life extension and strengthening of metallic structures. ICE design and practice guide. Thomas Telford, London, ISBN 0-7277-3009-6 Pellegrino C, Modena C (2002) FRP shear strengthening of RC beams with transverse steel reinforcement. J Compos Construct, 6(2), 104-111.

Moy, S. S. J., & Nikoukar, F. (2002). Flexural behaviour of steel beams reinforced with carbon fibre reinforced polymer composite. In: Shenoi RA, Moy SSJ, Hollaway LC (eds) Advanced polymer composites for structural applications in construction. Proceedings of ACIC2002, inaugural international conference on the use of advanced composites in construction. Thomas Telford, London, pp. 195-202.

Moy, S. S. J., & Lillistone, D. (2006). Strengthening cast iron using FRP composites. Proc Inst Civil Eng (ICE) Struct Build, 159(6), 309-318. http://dx.doi.org/10.1680/stbu.2006.159.6.309

Moy, S. S. J., & Bloodworth, A. G. (2007). Strengthening a steel bridge with CFRP composites. Proc Inst Civil Eng (ICE) Struct Build, 160, 81-93. http://dx.doi.org/10.1680/stbu.2007.160.2.81

Pellegrino, C., Pipinato, A., & Modena, C. (2011). A simplified management procedure for bridge network maintenance. Structure and Infrastructure Engineering, 7(5), 341-351. http://dx.doi.org/10.1080/15732470802659084
Pipinato, A. (2010). Step level procedure for remaining fatigue life evaluation of one railway bridge. Baltic Journal of Road and Bridge Engineering, 5(1), 28-37. http://dx.doi.org/10.3846/bjrbe.2010.04

Pipinato, A. (2011). Assessment of existing bridges: Safety and security issues [Problemi di sicurezza nelle valutazioni strutturali di ponti esistenti]. Ingegneria Ferroviaria, 66(4), 355-371.

Pipinato, A. (2012c). Coupled safety assessment of cable stay bridges. Modern Applied Science, 6(7), 64-78. http://dx.doi.org/10.5539/mas.v6n7p64

Pipinato, A., & Modena, C. (2010). Structural analysis and fatigue reliability assessment of the Paderno bridge. Practice Periodical on Structural Design and Construction, 15(2), 109-124. http://dx.doi.org/10.1061/(ASCE)SC.1943-5576.0000037

Pipinato, A., Molinari, M., Pellegrino, C., Bursi, O. S., & Modena, C. (2011a). Fatigue tests on riveted steel elements taken from a railway bridge. Structure and Infrastructure Engineering, 7(12), 907-920. http://dx.doi.org/10.1080/15732470903099776

Pipinato, A., Pellegrino, C., Bursi, O. S., & Modena, C. (2009). High-cycle fatigue behavior of riveted connections for railway metal bridges. Journal of Constructional Steel Research, 65(12), 2167-2175. http://dx.doi.org/10.1016/j.jcsr.2009.07.023

Pipinato, A., Pellegrino, C., & Modena, C. (2012b). Fatigue assessment of highway steel bridges in presence of seismic loading. Engineering Structures, 33(1), 202-209. http://dx.doi.org/10.1016/j.engstruct.2010.10.008

Pipinato, A., Pellegrino, C., & Modena, C. (2010). Structural analysis of historical metal bridges in Italy. Advanced Materials Research, 133-134, 525-530. http://dx.doi.org/10.4028/www.scientific.net/AMR.133-134.525

Pipinato, A., Pellegrino, C., & Modena, C. (2011b). Fatigue assessment of highway steel bridges in presence of seismic loading. Engineering Structures, 33(1), 202-209. http://dx.doi.org/10.1016/j.engstruct.2010.10.008

Pipinato, A., Pellegrino, C., & Modena, C. (2012a). Assessment procedure and rehabilitation criteria for the riveted railway Adige Bridge. Structure and Infrastructure Engineering, 8(8), 747-764. http://dx.doi.org/10.1080/15732479.2010.481674

Pipinato, A., Pellegrino, C., Fregno, G., & Modena, C. (2012b). Influence of fatigue on cable arrangement in cable-stayed bridges. International Journal of Steel Structures, 12(1), 107-123. http://dx.doi.org/10.1007/s13296-012-1010-5

Pipinato, A., Pellegrino, C., & Modena, C. (2012d). Life assessment of riveted bridges: an analytical approach. ICE-Bridge Engineering, UK Institution of Bridge Engineers. In print.

Rizkalla, S., Dawood, M., & Schnerch, D. (2008). Development of a carbon fiber reinforced polymer system for strengthening steel structures. Compos Part A Appl. Sci. Manufact, 39(2), 388-397. http://dx.doi.org/10.1016/j.compositesa.2007.10.009

Shaat, A., Schnerr, D., Fam, A., & Rizkalla, S. (2004). Retrofit of steel structures using Fiber-Reinforced Polymers (FRP): state-of-the-art. In: Transportation research board (TRB) annual meeting. CD-ROM (04-4063).

Shaat, A., & Fam, A. (2006). Axial loading tests on short and long hollow structural steel columns retrofitted using carbon fibre reinforced polymers. Can J. Civil Eng., 33(4), 458-470. http://dx.doi.org/10.1139/l05-042

Schnerr, D., Dawood, M., Rizkalla, S., & Sumner, E. (2007). Proposed design guidelines for strengthening of steel bridges with FRP materials. Construct Build Mater, 21, 1001-1010. http://dx.doi.org/10.1016/j.conbuildmat.2006.03.003

Schnerr, D., & Rizkalla, S. (2008). Flexural strengthening of steel bridges with high modulus CFRP strips. J. Bridge Eng., 13(2), 192-201. http://dx.doi.org/10.1061/(ASCE)1084-0702(2008)13:2(192)

Sen, R., Liby, L., Spillett, K., & Mullins, G. (1995). Strengthening steel composite bridge members using CFRP laminates. In: Proceedings of the 2nd international RILEM symposium, FRPRCS-2, Aug. 23-25, Ghent, Belgium.
Smith, S. T., & Teng, J. G. (2001). Interfacial stresses in plated beams. *Eng. Struct.*, 23, 857-871. http://dx.doi.org/10.1016/S0141-0296(00)00090-0

Stratford, T. J., & Cadei, J. M. C. (2006). Elastic analysis of adhesion stresses for the design of a strengthening plate bonded to a beam. *Construct Build Mater.*, 20(1-2), 34-45. http://dx.doi.org/10.1016/j.conbuildmat.2005.06.041

Taljsten, B. (1997). Strengthening of beams by plate bonding. *J. Mater Civil Eng.*, 9(4), 206-212. http://dx.doi.org/10.1061/(ASCE)0899-1561(1997)9:4(206)

Täljsten, B., Skodborg, C. H., & Wittrup J. S. (2001). Strengthening of old metallic structures in fatigue with prestressed and non-prestressed CFRP laminates. *Construction and Building Materials*, 23(2009), 1665-1677.

Tavakkolizadeh, M., & Saadatmanesh, H. (2003a). Strengthening of steel-concrete composite girders using carbon fiberreinforced polymer sheets. *J. Struct. Eng.*, 129(1), 30-40. http://dx.doi.org/10.1061/(ASCE)0733-9445(2003)129:1(30)

Tavakkolizadeh, M., & Saadatmanesh, H. (2003b). Repair of damaged steel-concrete composite girders using carbon fiber-reinforced polymer sheets. *J. Compos. Construct*, 7(4), 311-322. http://dx.doi.org/10.1061/(ASCE)1090-0268(2003)7:4(311)

Tavakkolizadeh, M., & Saadatmanesh, H. (2003). Fatigue strength of steel girders strengthened with carbon fiber reinforced polymer patch. *Journal of Structural Engineering, ASCE* 129(2), 186-196. http://dx.doi.org/10.1061/(ASCE)0733-9445(2003)129:2(186)

Yuana, H., Teng, J. G., Seracinoc, R., Wud, Z. S., & Yaoa, J. (2004). Full-range behavior of FRP-to-concrete bonded joints. *Engineering Structures*, 26(5), 553-565. http://dx.doi.org/10.1016/j.engstruct.2003.11.006

Zheng, Y., Ye, L. P., & Lu, X. Z. (2006). Experimental Study on Fatigue Behaviour of tensile plates strengthened with CFRP plates. Third International Conference on FRP Composites in Civil Engineering (CICE 2006).

Zhao, X. L., & Zheng, L. (2007). State-of-the-art review on FRP strengthened steel structures. *Eng. Struct.*, 29, 1808-1923. http://dx.doi.org/10.1016/j.engstruct.2006.10.006