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Carbon Fibre Reinforced Polymer Fatigue Strengthening of Old Steel Material

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ABSTRACT:
This paper reports the experimental results of a study investigating the effect of reinforcing metallic structures with carbon fibre reinforced polymer (CFRP) to increase their fatigue life. In the study, samples made of puddled steel and mild S235JR grade steel reinforced with CFRP strips were examined. The samples were subjected to tensile fatigue loading with a stress ratio R of 0.115 and 0.130 (mild steel samples) and 0.13/1.25/0.15/1.07 (puddled steel samples). A total of 9 samples with CFRP/steel single overlap joints and 20 reference specimens were tested to determine their fatigue life and failure modes. Normal modulus CFRP strips with one cross section (20×1.4 mm) were used in this study. Laboratory test results showed that CFRP strengthening had a visible effect on the fatigue life of the steel samples. The application of adhesive-bonded CFRP laminates significantly prolonged the fatigue life of the specimens. The increase in the fatigue life of the steel samples reinforced with CFRP strips was 2 to 16 times (for mild steel) and 11 to 28 times (for puddled steel) higher than those of the non-reinforced specimens.

Keywords: puddled steel, mild steel, CFRP laminate, fatigue test, fatigue strengthening.

INTRODUCTION

Apart from corrosion, fatigue is one of the main causes of failure of metal bridges. According to Hołowaty et al. [1], over 75% of railway bridges in Poland are more than 50 years old, and almost 45% of them have been in operation for over 100 years, which is beyond the current standards for service life. Nowadays a large part of the world's steel railway structures are in unsatisfactory technical condition, according to Bocciarelli et al. [2] and Colombi and Fava [3]. Some of the old steel bridges are nearing the end of their expected fatigue life, as pinpointed by Cremona et al. [4] and Siriwardane [5]. It should be noted that these bridges make a constituent part of engineering structures in operational railway networks. Old metal railway bridges are characterized by materials they are made of, such as wrought iron, puddled steel, welding steel, and mild steel. The main feature of these metal structures are riveted joints. Rivet holes are the area of potential crack initiation under fatigue loading. According to Brûhwiler et al. [6], cracks occur almost exclusively at or near rivet holes in rolled girders with riveted coverplates and in riveted plate girders. In riveted lattice girders cracks also form in rivets and diagonal elements or – as demonstrated by Haghani et al. [7] – they usually start at the outstanding leg of a connection angle and grow along the fillet of the angle. According to Åkesson [8], several potential fatigue critical regions can be identified in riveted bridges where fatigue may be more likely to occur. These include the connections between vertical floor-beam tension hangers and horizontal top compression bars (in a truss bridge); lower tension flange rivets at midspan (in a stringer); the outstanding leg of the top compression flange (which is a potential fatigue critical member part in a stringer); lower tension flange rivets at the midspan between the stringer connections (in a floor beam), as well as extreme upper and lower rivets in the connection between a stringer and a floor beam (in a stringer-to-floor-beam connection).

Conventional passive repair methods involve increasing the cross-section of a given element by adding steel plates to the damaged element. Depending on possibilities, these additional elements are welded, screwed to prestressed bolts or riveted (the latter being less frequently used in Poland, if at all). Passive increase in the cross-section of an element can however have negative effects [9], including the induction of additional permanent loads, formation of new areas of stress concentration, changes in the static diagram of a reinforced element, and neutral axis displacement. Moreover, these additional reinforcement elements are subject to the same fatigue and corrosion phenomena, as reported by Lepretre et al. [10]

An alternative to the currently used conventional methods of strengthening steel structures is to use carbon fibre reinforced polymer (CFRP) composite materials. CFRP composites exhibit high tensile strength and high longitudinal stiffness. They are about four times lighter than steel, which is an advantage when these materials are adhesive-bonded to the bottom of an element. According to Bocciarelli et al. [2] and Colombi and Fava [3], the fatigue strength of composites that are adhesive-bonded to damaged elements as reinforcement is higher than that of welded steel plates. Early studies on CFRP steel strengthening mainly focused on the strength of quasi-statically loaded structures reinforced with different CFRP configurations [11–15]. A co-author of this study also dealt with this problem in his doctoral dissertation [16], [17]. Research has also been conducted on strengthening steel structure to increase their resistance to fatigue loads [18–22]. Previous studies assessing the effect of reinforcing steel with CFRP composites on reducing crack development and extending fatigue life have been carried out on both small and large samples. To our knowledge, few studies have focused on the problem of strengthening elements of old objects, e.g. those that are over one hundred years old.

Taljsten et al. [23] performed tests on notched samples made from the web of an old mild steel bridge spar. The samples were reinforced with compressed and uncompressed CFRP laminates. They tested samples with a double-sided reinforcement and various CFRP laminates. It was shown that pre-compressed CFRP laminates could stop crack propagation. Hosseini et al. [24] found that the crack arrest was only possible when prestressed CFRP reinforcements with a certain level of prestressing were used in a prestressed unbonded normal-modulus CFRP reinforcement specimen. They concluded that the efficiency of the prestressing force in CFRP reinforcements was much higher than the stiffness effect of the reinforcement for fatigue strengthening of cracked steel members.

Previous research has also focused on the use of uncompressed CFRP laminates with Young's High Modulus (HM) and Ultra High Modulus (UHM). Wu et al. [25] investigated the reinforcement of notched steel plates with UHM CFRP laminates attached on both sides in different adhesive configurations. They achieved fatigue strength increase from 3.26 to 7.47 depending on the configuration. The best results were obtained when the CFRP reinforcement covered the entire crack. In reality, however, especially with riveted joints, this reinforcement configuration is not very plausible. Even better results were achieved by Borrie et al. [26]. For a double-sided reinforcement, they obtained an over 24-fold increase in fatigue strength, and after aging the fatigue strength of the samples increased by over 16.8 times.

Apart from prestressed CFRP tapes, laminates with a higher CFRP modulus and double-sided reinforcement are most effective in increasing fatigue life. This effect was obtained for a double-sided reinforcement configuration using CFRP mats [20], [27] and CFRP tapes with both a normal [28] and a very high modulus [25].

Due to the complexity of cases in engineering practice, fracture and fatigue under mixed-mode loading have also been investigated for steel [29], [30] and aluminium alloy [31]. For fatigue life tests under multiaxial loading, multiaxial fatigue failure criteria are most often applied, these criteria being defined in time and frequency domain [32]. Advanced control systems for fatigue machines are also necessary to generate complex loads [33]. Moreover, nowadays, additively manufactured metallic structures are studies in order to establish a relationship between their manufacturing parameters and fatigue behaviour [34]–[36]. In most studies to date, specimens are usually metal flat bars with a central hole and one or two symmetrical slots on each edge of the hole across the flat bar [37], [38]. Chen et al. conducted tests on specimens with a central notch and crack starters at different angles to the transverse axis of the flat bar. Straight notch specimens were also tested in [39]. However, these types of specimens are not representative of broken rivets where most often only one fatigue crack is formed from the rivet hole. To assess the effectiveness of CFRP reinforcement in old cracked riveted elements, small specimens of old metal plates with one crack emerging from the rivet hole were tested in [10]. Two metallic materials were considered: plain mild steel and wrought iron removed from an old girder bridge.

The objective of experiments performed in this study was to determine the effect of CFRP strengthening on the fatigue life increase in both modern mild steel and over 100-year-old puddled steel. Dumbbell-shaped test specimens were used in the experiments, which resulted from the research capacity and the limited availability of the material. The experiments were considered to be a preliminary to a more complex research program on strengthening steel with composites for fatigue loads.

EXPERIMENTAL SET-UP

Test specimens

Preliminary static tensile tests were conducted on dumbbell-shaped specimens with notches on both sides, see Figs. 1 and 2. 11 specimens made of mild steel and 14 specimens made of puddled steel were tested. The mild steel specimens were made as shown in Figure 1, and the puddled steel specimens as in Figure 2. The mild steel specimens were cut from 10 mm thick sheets. The puddled steel samples were obtained by water cutting from different structural elements of a more than 100-year-old railway bridge (more details can be found in [40]). After that, notches were milled on the samples to ensure they would get damaged in the most weakened region of the cross section. As it is typical of this type of research, the shape and varied thickness of the samples resulted from the limited availability of the starting material (an over 100-year-old bridge). The steel samples of a hundred-year-old object and the mild steel samples were prepared for other research purposes.

Two types of double-sided notches were made in the samples. They do not represent the actual fatigue crack induced by making a rivet hole, because an analysis of fatigue crack development was not the aim of this study. The effect of CFRP fatigue strengthening was assessed depending on the degree of reinforcement with adhesive-bonded composites. Moreover, prestressed riveted joints, whatever the number of rivets in a line, have a greater fatigue strength than plates with free holes. [10] Given the fact that the production of samples with a hole and a notch was not feasible, it was assumed that the test samples with external notches would be prepared for the purpose of this study.

All specimens were reinforced with CFRP laminates along the entire length over a width of 20 mm. All specimens were patched on one side. With real elements of riveted objects it is often possible to apply reinforcement to only one side of the element. Therefore, the unilaterally reinforced samples described in this study can be considered representative.

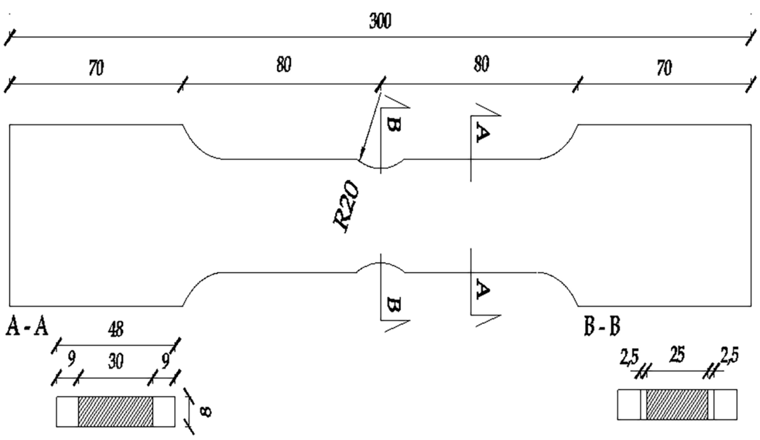

Figure 1. Scheme of a sample made of S235JR mild steel

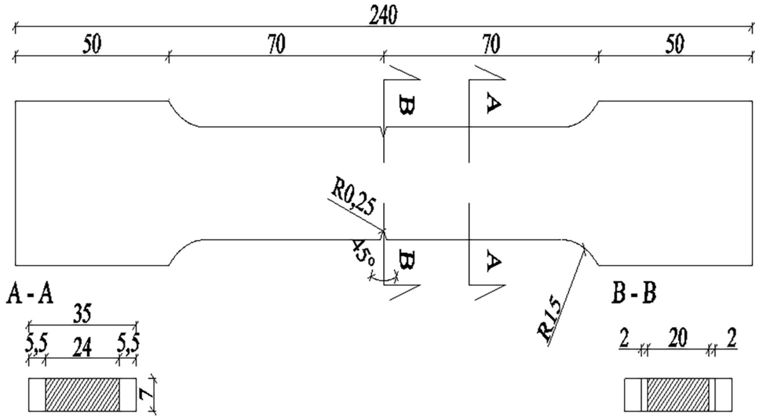

Figure 2. Scheme of a sample made of over 100-year-old steel (puddled steel)

Material properties

Mechanical properties of the metallic plates were determined through tensile coupon tests. The S235JR carbon steel grade was used owing to its properties and the fact that they closely resemble those of mild steel that is present in old structures. The mechanical properties of this material were tested under quasi-static loading. The measured yield strength and tensile strength were $R_{eH} = 287.1$ and $R_m = 432.0$ MPa, respectively. Puddled steel specimens were fabricated from different plate components that were obtained following the dismantling of an old riveted railway bridge described in [40]. Their measured yield strength and tensile strength were $R_{eH} = 265.3$ and Rm = 354.0 MPa, respectively.

In this study, one type of unidirectional NM (Normal Modulus) CFRP was used. S&P Lamelle CFK 200/2000 normal modulus CFRP unidirectional plates with their own bi-component epoxy adhesive S&P Resin 220 were used as patching systems. The tapes had a width of 20 mm and a thickness of 1.4 mm. Specimens with normal modulus CFRP were prepared to determine their tensile mechanical properties. Obtained mechanical properties were compatible with those reported by the manufacturer. The obtained ultimate tensile strength, ultimate strain and elastic modulus were 2500 MPa, 1.25% and ≥ 210.0 GPa, respectively. A system adhesive S&P Resin 220 was used to adhesive bond the composite tapes. Their elastic modulus was 10.7 GPa, tensile strength 11.4 MPa, shear strength ≥ 26.0 MPa, peel strength on the tape S&P Lamellen ≥ 3.0 MPa, steel on steel ≥ 14.0 MPa, as claimed by the manufacturer in the technical sheet.

Specimen preparation

The bonding surface of the metallic plates was sandblasted first and then carefully cleaned with acetone. The CFRP plates were wiped with acetone before bonding them to steel. CFRP laminates were then attached to the sandblasted steel surface using the S&P Resin 220. The strips were pressed with a steel mould designed in such a way that the excess adhesive would flow out from under them. The total thickness of the CFRP strips and adhesive was maintained constant over the entire length of the strips. Adhesive excess was removed. On the next day, textolite overlays were adhesive-bonded to the reinforcement tape at the anchorage in the testing machine in order to prevent CFRP tape damage by the jaws during the tests. The samples were tested after one week of storage at room temperature. The measured average thickness of the adhesive in the S235JR steel samples was 1.11 mm, while in the 100-year-old steel samples it was 1.05 mm. An exemplary photo of a mild steel sample is shown in Fig. 3. The employed method of anchoring resulted from the need for mechanical anchoring of the tape. If the tapes had been adhesive-bonded without anchoring, they would have detached from the steel samples immediately after switching on fatigue load. This was due to a too high range of fatigue loads. A photo of reinforced specimens with notches made of 100-year-old steel is shown in Figure 4. Denotations in Figure 3 (e.g. 15.115.4) define the fatigue load range, i.e. the percentage of the upper yield strength (0.15 R_{eH}; 1.15 R_{eH}), and the number of the tested sample from the population.

Denotations in Figure 4 (e.g. WS.06.4) describe the sample type (for this case, samples WS were prepared for static tests), the element from which the sample was taken (04,10 – belt, 03, 06

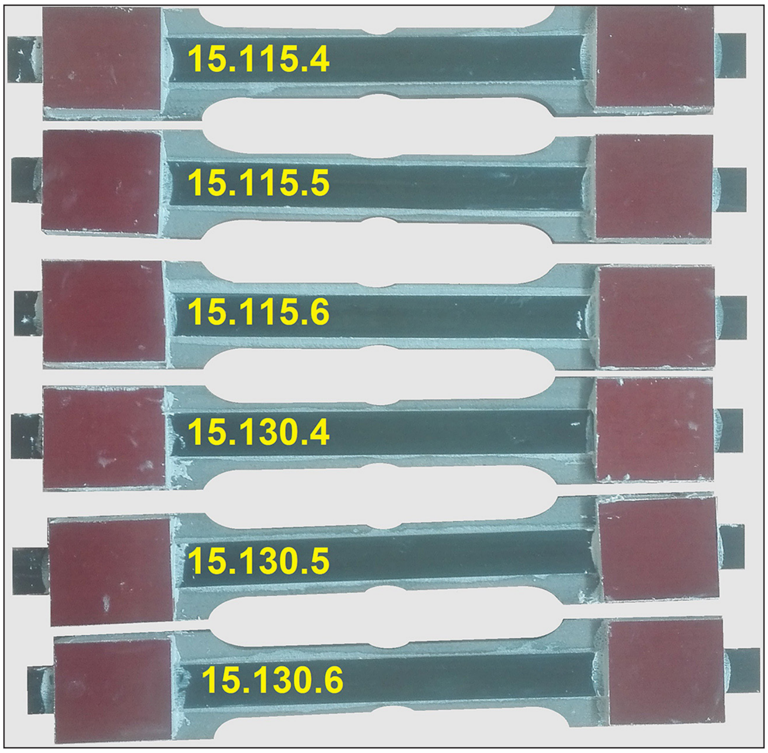

Figure 3. Reinforced samples made of S235JR mild steel

– wind girder, 1, 9, 11 – crossbar, 05, 07 – bracing of the stringers, 02 – stringers), and the number of the sample from a given element.

Fatigue loading procedure

Fatigue tests were carried out on the MTS 319.25 testing machine with a maximum tensile capacity of 250 kN. All specimens made of S235JR steel were subjected to uniform cyclic loading with a constant frequency of 20 Hz. The S235JR steel specimens were subjected to a stress ratio R of 0.115 and 0.130 until their complete failure. The reinforced specimens of old steel were subjected to a stress ratio R 0.13 until complete failure. The stress ratio was defined as a ratio between the minimum stress and the maximum stress applied to the specimen in the fatigue test. Different stress ranges were used: 0.15÷1.15 R_{eH} and 0.15÷1.30 R_{eH} in the nominal section of the S235JR steel specimens and 0.15÷1.15/1.20/1.30/1.40 R_{eH} for the reinforced

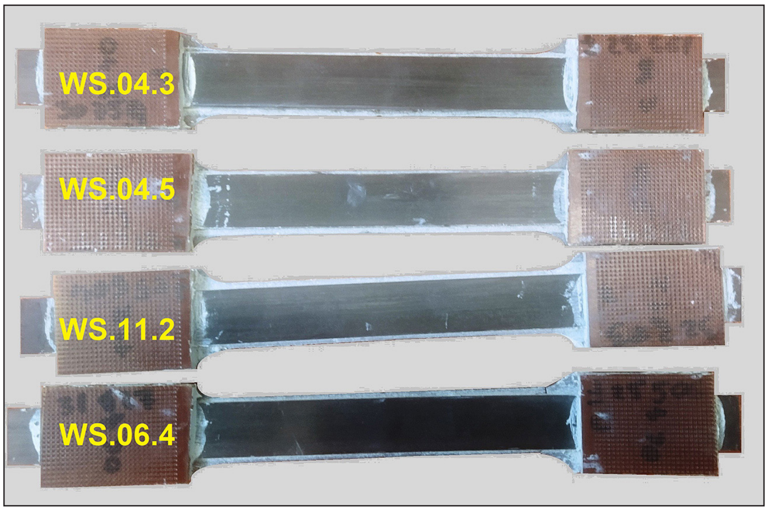

Figure 4. Reinforced samples made of 100-year-old steel

old steel specimens. The stress range corresponded to the applied load ranges of 9–69.8 kN and 9–79.2 kN for the mild steel specimens (8 mm thick plate) and 6.1–57.9 kN for the old steel specimens (6 and 7 mm thick plates). The tests were performed with a slow sine wave amplitude growth at the early stage of the experiment. PVC compensation was enabled to ensure proper test conditions. Time consumption in the preliminary test was considerably reduced by applying a high range of loads.

For the non-reinforced old steel specimens, fatigue testing [40] was carried out in the stress ranges from 0.118÷0.166 to 0.889÷1.204 R_{eH}. The specimens made of old steel were put under a stress ratio R of 0.098÷0.152 until their complete failure.

RESULTS AND DISCUSSION

Obtained experimental results are listed in Tables 1 and 2 for the mild steel specimens and in Tables 3 and 4 for the wrought iron specimens

The mild steel samples were subjected to two ranges of fatigue load. Fatigue loading in the range of 0.15÷1.30 R_{eH} caused the failure of the samples after an average of 6,862 fatigue cycles. Fatigue loading in the range of 0.15÷1.15 R_{eH} caused the failure of the samples after an average of 126,236 fatigue cycles.

The mild steel specimens reinforced on one side with a CFRP composite tape were subjected to the same fatigue load ranges as the non-reinforced specimens. The fatigue loading of the samples in the range of 0.15 ÷ 1.30 R_{eH} resulted in the failure of the reinforced samples after an average of 110,871 fatigue cycles. Fatigue loading of the reinforced samples in the range of 0.15 ÷ 1.15 R_{eH} resulted in the failure of the samples after an average of 261,643 fatigue cycles.

The hundred-year-old steel samples were subjected to several ranges of fatigue load. The use of the different load ranges resulted from different material properties of the puddled steel elements depending on the structural element from which the samples were cut. The yield point and tensile strength differed for the elements of chords, crossbars and diagonals, and wind girders. The fatigue loading of the samples was carried out in the ranges close to 0.15 ÷ 1.14 R_{eH}, 0.15 ÷ 1.17 R_{eH} and 0.13 ÷ 1.02 R_{eH} (R = 0.131) and 0.16 ÷ 1.09 R_{eH} (R = 0.151). The fatigue loading of the samples in the range close to 0.15 ÷ 1.14 R_{eH} resulted in the failure of the samples following 13,719 and 89,381 fatigue cycles. The fatigue loading of the samples in the range close to 0.15 ÷ 1.17 R_{eH} resulted in the failure of the samples after 169,256 and 187219 fatigue cycles. The sample loaded in the lowest range of 0.13 ÷ 1.02 R_{eH} was damaged after 106,557 fatigue cycles.

Table 1. Fatigue life of non-reinforced S235JR mild steel specimens

Spec. no.	R_{eH} [Mpa]	R_{eH} range			σ range [Mpa]			R	No. of cycles
15.115.1	287.1	0.15	÷	1.15	43.1	÷	330.2	0.130	128659
15.115.2									138100
15.115.3									111950
15.130.1		0.15	÷	1.30	43.1	÷	373.2	0.115	6522
15.130.2									7917
15.130.3									6146

Note: Nomenclature as in Fig. 3.

Table 2. Fatigue life of reinforced S235JR mild steel specimens

Spec. no.	R_{eH} [MPa]	R_{eH} range			σ range [MPa]			R	No. of cycles
15.115.4	287.1	0.15	÷	1.15	43.1	÷	330.2	0.130	256027
15.115.5									267260
15.130.4		0.15	÷	1.30	43.1	÷	373.2	0.115	143373
15.130.5									98644
15.130.6									90595

Figure 5. CFRP-reinforced mild steel samples subjected to fatigue load in the range 0.15÷1.15 R_{eH}

The hundred-year-old steel samples reinforced with CFRP were subjected to four ranges of fatigue load (0.15 ÷ 1.15 R_{eH}; 0.15 ÷ 1.20 R_{eH}; 0.15 ÷ 1.30 R_{eH}; 0.15 ÷ 1.40 R_{eH}). This time the application of different load ranges resulted from the necessity to consider the amplification effect. The fatigue loading of the sample in the range of 0.15 ÷ 1.14 R_{eH} (R = 0.13) resulted in its failure after 2,201,640 fatigue cycles. The fatigue load of the sample in the range of 0.15 ÷ 1.20 R_{eH} (R = 0.124) caused the failure of the sample after 2,067,544 fatigue cycles. The fatigue loading of the sample in the range of 0.15 ÷ 1.30 R_{eH} (R = 0.116) resulted in the failure of the sample after 296354 fatigue cycles. The fatigue loading of the sample in the range of 0.15 ÷ 1.40 R_{eH} (R = 0.107) resulted in the failure of the sample after 567 390 fatigue cycles.

After Kowal and Szala [40], the scope of the fatigue tests also included using a different type of dumbbell-shaped test specimens which were prepared in accordance with the ASTM standard for fatigue strength tests. These results are provided for informational purposes only in Table 5. Samples of this type cannot be reinforced in accordance with the assumptions of this study, i.e. by adhesive-bonding a composite tape.

Denotations in Table 5 (e.g. WZ.04.6) describe the type of sample (for this case, specimens WZ were prepared for fatigue tests according to

Figure 6. CFRP-reinforced mild steel samples subjected to fatigue load in the range 0.15÷1.30 R_{eH}

the ASTM E468–11standard), other denotations as in Figure 4.

An assessment of the obtained fatigue test results is neither simple nor unambiguous. The fatigue strength tests were carried out in order to determine this parameter in an over century-old steel material which had previously been subjected to unknown loads. According to the ASTM E468–11 standard, the material should transfer 1×10^7 fatigue cycles so that its fatigue strength can be determined within a given load range. In this study, the test was stopped due to obtaining over 2×10^6 fatigue cycles (EN1993–2:2006). This value is required for the whole steel bridge structure. It is worth noting that more than 2×10^6 fatigue cycles were obtained for only one sample for the load range of 0.12÷0.89 R_{eH}. The upper limit is only slightly higher than the required value of steel design strength $R_{eD}=R_{eH}/\gamma=R_{eH}/1.15=0.87R_{eH}$. It could therefore be inferred that – in an extreme case – the structure would withstand the required number of fatigue cycles. There is no data about the actual payloads which the bridge had been subjected to until the end of its use. It is also unknown how many of these load cycles the bridge structure had experienced. An analysis of the data in Tables 3 and 5 reveals that there is no repeatability of fatigue life results. The upper limit of the load range indicates ambiguity regarding the number of fatigue cycles withstood by the samples cut from various structural components of the bridge. This may be caused by both the aging of the object and the microstructural uniformity of steel. Based on the fatigue test results, however, it can be claimed that, without the reinforcement, the structure would not have been able to transfer a greater static load or increase the upper limit of the amplitude of fatigue loads [40].

The obtained fatigue life values correspond to the number of fatigue cycles counted from the initial pre-crack until complete failure. In this experimental program, the specimens described in Table 1 (mild steel) and Table 3 (puddled steel) were used as reference specimens, i.e. without reinforcement.

Since the mild steel specimens showed high repeatability of the results, the fatigue life of each reinforced specimen was compared with the average fatigue life of the reference specimens, and the ratio between them was referred to as a fatigue life increase ratio. For each tested reinforcement configuration, the average fatigue life increase ratio is marked in bold in Table 6.

An analysis of the data in Table 6 demonstrates that compared to the non-reinforced samples, the fatigue life of the mild steel specimens considerably increased with a higher range of fatigue load. The data obtained for the mild steel specimens show that their fatigue life increased by even several times depending on the output fatigue load. For the samples with a fatigue load range of 0.15 ÷ 1.30 R_{eH}, the obtained fatigue life

Table 3. Fatigue life of non-reinforced puddled steel specimens

Spec. no.	R_{eH} [MPa]	R_{eH} range			σ range [MPa]			R	No. of cycles
WS.02.1	309	0.149	÷	1.136	46	÷	351	0.131	13719
WS.10.2	309	0.149	÷	1.136					71185
WS.06.2	249	0.149	÷	1.140					89381
WS.04.1	294	0.134	÷	1.023					106557
WS.11.4	299	0.154	÷	1.174					169256
WS.03.3	300	0.153	÷	1.170					187219
WS.08.3	279	0.165	÷	1.093	46	÷	305	0.151	316246

Note: Nomenclature as in Fig. 4.

Table 4. Fatigue life of reinforced puddled steel specimens

Spec. no.	R_{eH} [MPa]	R_{eH} range			σ range [MPa]			*R*	No. of cycles
WS.04.3	294	0.15	÷	1.15	44.1	÷	338.0	0.130	2021640
WS.04.5	294	0.15	÷	1.20	43.9	÷	352.8	0.124	2067544
WS.06.4	249	0.15	÷	1.40	37.3	÷	348.8	0.107	567390
WS.11.2	270	0.15	÷	1.30	40.6	÷	351.1	0.116	296354

a)

b)

Figure 7. Damaged puddled steel samples reinforced with CFRP

increase ratio amounts to 16.158. For the samples with a lower fatigue load range of 0.15 ÷ 1.15 $R_{eH,}$ the obtained fatigue life increase ratio equals 2.073. As shown in Table 6, at least a two-fold increase in fatigue life was obtained with increasing the cross-section by 13.5 ÷ 13.8%. For both cases, the fatigue life level of $2*10^6$ cycles (which is expected from bridge structures) was not achieved. This, however, proves that the starting level of fatigue load was too high, as previously mentioned.

As for the puddled steel specimens, for which a wide scatter of the results was observed, the fatigue life increase ratio was defined as a fatigue life of the reinforced specimen divided by the maximum value of fatigue life obtained for the non-reinforced specimen in relation to the R_{eH} range, see Table 7.

For the non-reinforced samples, for which the R_{eH} range was below 0.15÷1.09 R_{eH} or above 0.15÷1.20 R_{eH}, the fatigue life ratio increase was not determined. The loading ranges of the reinforced samples amounting to 0.15÷1.15 R_{eH} and 0.15÷1.20 R_{eH} were similar to the loading ranges of the non-reinforced samples, i.e. 0.15÷1.14 R_{eH} and 0.15÷1.17 R_{eH}. Therefore, they were used as a reference.

Table 5. Fatigue life of puddled steel specimens (for specimens prepared according to ASTM E468–11)

Spec. no.	R_{eH} [MPa]	R_{eH} range			σ range [MPa]			*R*	No. of cycles
WZ.04.6	343	0.117	÷	1.204	40	÷	413	0.097	326
WZ.02.1	309	0.129	÷	0.994	40	÷	307	0.130	277776
WZ.06.3	308	0.120	÷	0.929	37	÷	286	0.129	525361
WZ.04.2	343	0.128	÷	0.942	44	÷	323	0.136	806250
WZ.03.4	300	0.140	÷	1.077	42	÷	323	0.130	1318897
WZ.10.2	309	0.129	÷	0.961	40	÷	297	0.135	1679255
WZ.06.1	308	0.120	÷	0.890	37	÷	274	0.135	2050000

Table 6. Fatigue life increase ratio for mild steel specimens

Non-reinforced		Average fatigue life cycles	Reinforced		Average fatigue life cycles	Fatigue life increase ratio	Average fatigue life increase ratio
Spec. no.	No. of cycles		Spec. no.	No. of cycles			
15.115.1	128659	126236 (s=10812)	15.115.4	256027	261644 (s=5617)	2.028	2.073 (s=0.045)
15.115.2	138100		15.115.5	267260		2.117	
15.115.3	111950						
15.130.1	6522	6862 (s=762)	15.130.4	143373	110871 (s=23216)	20.895	16.158 (s=3.384)
15.130.2	7917		15.130.5	98644		14.376	
15.130.3	6146		15.130.6	90595		13.203	
s – standard deviation							

For the puddled steel samples, the fatigue life increase ratio was 11.600 for the fatigue load range of 0.15 ÷ 1.20 R_{eH}. For the fatigue load range of 0.15÷1.15 R_{eH}, the fatigue life increase ratio amounted to 34.799. In Table 7 are listed the results obtained with increasing the cross-section of the reinforced element by 17.4 ÷ 20.5%.

A comparison of the data obtained for 100-year-old steel and mild steel reveals a large scatter of the results. This can be explained by the differences in the microstructure of the tested materials, as puddled steel has a large amount of brittle inclusions in its structure. However, a high fatigue life increase ratio was obtained for all reinforced samples in the range from 11.6 and 34.799. Contrary to the mild steel samples, no effect of the degree of damage could be observed for the old steel samples due to the large scatter of the results. The results obtained for both materials (mild steel and puddled steel) cannot be directly compared due to the differences in the cross-sectional areas of the samples – specifically, the cross-sectional area for mild steel was about 210 mm^2 with a thickness of about 8.1 mm while for puddled steel it was about 138 mm^2 and 163 mm^2 with a thickness of about 6 and 7 mm. The results showed that the application of reinforcement with CFRP strips had a greater effect on stress reduction when smaller sections of steel plates were strengthened. These results are consistent with those reported by Lepretre et al. [10] and Liu [20] and Emdad and Al-Mahaidi [41]. Nevertheless, it is difficult to compare the results obtained in this study with experimental results reported in other studies due to differences in notches and reinforcement configurations of CFRP tapes. These experiments are also an introduction to more extensive research on samples with a notch made as a scratched hole.

CONCLUSIONS

This experimental study investigated the fatigue behaviour of cracked metallic plates reinforced with adhesive-bonded CFRP laminates. In the study, the fatigue behaviour of 8 mm thick mild steel and 7 mm thick puddled steel specimens was examined, each specimen having two symmetrical notches on the outside and being reinforced

Table 7. Fatigue life increase ratio for puddled steel specimens

Non-reinforced					Reinforced					Fatigue life increase ratio
Spec. no.	R_{eH} range			No. of cycles	Spec. no.	R_{eH} range			No. of cycles	
					WS.06.4	0.15	÷	1.40	567390	*
					WS.11.2	0.15	÷	1.30	296354	*
WS.03.3	0.15	÷	1.17	187219	WS.04.5	0.15	÷	1.20	2067544	11.600
WS.11.4	0.15	÷	1.17	169256						
WS.02.1	0.15	÷	1.14	13719	WS.04.3	0.15	÷	1.15	2021640	34.799
WS.10.2	0.15	÷	1.14	71185						
WS.06.2	0.15	÷	1.14	89381						
WS.08.3	0.17	÷	1.09	316246						*
WS.04.1	0.133	÷	1.023	106557						*
* No optimal comparison of fatigue life increase ratio results was feasible.										

with unidirectional NM (Normal Modulus) CFRP laminates that were bonded to one side of the metallic plate. The following conclusions have been drawn from the results of the study. The application of adhesive-bonded CFRP laminates significantly prolonged the fatigue life of specimens. The fatigue life of the CFRP-reinforced mild steel specimens increased by 2.073 and 16.158. The fatigue life increase was obtained with increasing the cross-section of the specimens by 13.5 ÷ 13.8%. The fatigue life of the CFRP-reinforced puddled steel specimens increased by 11.600 and 34.799. The fatigue life increase was obtained with increasing the cross-section of the reinforced elements by 17.4 ÷ 20.5%. A high scatter of the results was observed for all specimens, which was mainly due to the microstructure of puddled steel, see [40]. However, with safety factors taken into account, the proposed method of reinforcement can be applied to old steel structures. Two different failure modes were observed depending on the specimen material. In all mild steel specimens, the composite tape underwent sudden rupture after the steel sample was completely damaged. The puddled steel specimens underwent scratching and breakage, but the tape did not break. This can be explained by different cross-sections of the reinforced samples and different levels of applied fatigue loads.

The tests described in the paper were a preliminary to fatigue stress testing of round-notch samples. Further research is needed to evaluate the effect of reinforcing steel samples with CFRP composites. It is necessary to investigate different reinforcement configurations and their effect on the extension of fatigue life under more realistic fatigue load ranges. This should help determine combinations of reinforcement configurations and anchorage lengths of composite strips allowing for non-mechanical anchoring. Such methods will be useful in engineering practice and may be adapted to elements with other geometries, e.g. riveted joints.

The results of this study can be useful in engineering practice. Adhesive-bonded CFRP composite materials are more and more widely used for strengthening steel structural components in order to increase their resistance to static and fatigue loads. The results show that a slight increase in the cross-section of an element reinforced with an adhesive-bonded CFRP composite tape leads to a proportionate increase in the fatigue life of the reinforced element. The speed and ease of application of in-situ composite reinforcement provides a wide range of possibilities in the event of a need for emergency reinforcement. The use of this type of ad-hoc reinforcement method allows for a better preparation of a long-lasting reinforcement such as a reinforcement with an adhesive-bonded CFRP composite material.

The main limitations of the proposed research method are as follows: appropriate weather conditions are required for substrate preparation, i.e. there must be no precipitation or positive temperature when the elements are adhesive-bonded; it is necessary to use appropriate mechanical or non-mechanical anchoring depending on the need; the impact of material aging on the load-bearing capacity of the system must be taken into account; it is necessary to consider the impact of changing weather conditions on the weakest link in the system, i.e. the adhesive, especially at low temperatures and when the temperature is below zero degrees Celsius.

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