Application of carbon FRP for fatigue strengthening of old steel structures

J Vůjtěch, P Ryjáček and M Vovesný
Faculty of Civil Engineering, Czech Technical University in Prague, 166 26 Prague, Czech Republic
E-mail: jan.vujtech@fsv.cvut.cz

Abstract. The traffic requirements on the existing infrastructure are rising still. This coupled with its age puts a strain on it. This is especially problematic for old steel bridges. Higher and more frequent loads will lead to development of fatigue damage to those structures. This causes an issue for the infrastructure owners as the existing methods of repair are difficult, time consuming and expensive. So there is a need to find some easier alternatives. One of such can be the use of carbon fibre reinforced polymers (CFRP). They are being successfully used for repairs and strengthening of concrete structures however their use with steel is still relatively new.

The purpose of this work is to establish how does a deteriorated steel reinforced with CFRP behave under fatigue loading. To test this a series of experiments was designed. With the help of a preliminary numerical study the dimensions of the specimens and the applied loading was established. There are two sets of specimens. With both we are using mild steel and each set has different level of surface deterioration (corrosion pits or corrosion holes). The specimens are reinforced using hand laid wet layup composites. They are subjected to fatigue loading and the difference between the fatigue life reinforced and unreinforced specimens is observed. Based on the preliminary study, it is expected, that the reinforcement will prolong the life expectancy by half.

1. Introduction
The current infrastructure in many countries in Europe is slowly reaching its life expectancy. This is particularly true for the steel bridges many of which was built at the turn of the 19th century. That brings many issues to the infrastructure owners. The two main of those would be the corrosion and fatigue cracks. They are especially dangerous because one can feed the other. The corrosion increases the likelihood of cracks mainly by increasing the stress levels in the damaged surface. It was shown in experiments e.g. [1] the corrosion pits lead to localized plasticization in the defect even under small loads. And once existing the fatigue crack are extremely dangerous because of the possibility of sudden collapse.

The conventional ways to repair fatigue damage (replacement, welding) may not be always possible. Furthermore, the conventional method is usually quite expensive and time-consuming. It is also impossible to use it while the structure is under load, the subsequent closing of the repaired structure brings additional indirect costs. A possible way to find an easier method of repair is the use of new construction materials, such as using externally bonded FRP. Which could become a fast and easy solution for extending the service life of the structure.
The fibre-reinforced polymer (FRP) is a composite with of two main components, matrix and fibres. Together they form a new material of very high strength and durability. Matrix is usually polyester, vinyl-ester or epoxy glue. The fibres (glass, carbon, kevlar etc.) form the reinforcement. For steel members just carbon fibres are viable, as their modulus of elasticity is similar to the steel. However, steel and carbon create galvanic cell and they have to be separated by epoxy resin or other means.

2. The experiments
Using the carbon fibres for reinforcing against fatigue is of course not entirely new. There have been several studies into this matter. To mention just a few articles published [2], [3] and for a state of art review see [4]. There are also several national guidelines, such as the British [5], US [6] and the Italian [7]. However, the research into this topic is still relatively new and does not cover everything. Much more additional research is required to fully understand the behaviour of reinforced elements in all possible scenarios.

In our research we focus on the fatigue life of a corroded steel specimen reinforced with the CFRP. For the experiments there are two sets of specimen prepared (see Table 1). Each set has a different type of deterioration which corresponds to two most common types of damage found on old steel structures. The first is heavy surface corrosion, the corrosion pits. On our specimens the corrosion is idealised so the corrosion pits are symmetrical. The second is heavy corrosion in the form of corrosion hole. Which can develop either with corrosion going through the whole element or around a rivet.

To establish the dimensions of specimens and the faults a preliminary numerical study was performed. The study was also used to establish the amount and type of reinforcement and the loading force that is going to be used. The results of this study were presented at conference Esat2016 [8].

Table 1. List of specimens

| Specimen Nr. | Fault | Surface treatment | Steel | Additional inf. |
|--------------|-------|-------------------|-------|-----------------|
| 1 - 4        | 1     | Sa 2 – sand blasting | mild  | Unreinforced    |
| 5 - 8        | 1     | Sa 2½ - sand blasting | mild  | Reinforced      |
| 9 - 12       | 2     | Sa 2 - sand blasting | mild  | Unreinforced    |
| 13 - 16      | 2     | St 2 - brushing    | mild  | Reinforced +100 freeze thaw cyc. |
| 17 - 20      | 2     | Sa 2½ - sand blasting | mild  | Reinforced      |
| 21 - 24      | 2     | Sa 2½ - sand blasting | mild  | Reinforced +100 freeze thaw cyc. |
| 33 - 36      | 1     | Sa 2½ - sand blasting | S355  | Reinforced      |
| 37 – 40      | 2     | Sa 2½ sand blasting | S355  | Reinforced      |
| 41 - 44      | 2     | Sa 2½ sand blasting | S355  | Reinforced +100 freeze thaw cyc. |
| 45 - 48      | 2     | Sa 2½ sand blasting | S355  | Reinforced      |

2.1. Specimen
The geometry is identical for both types of specimens. The specimen is a steel plate 500 mm long, 14 mm thick and with the width of 60 mm in the tested part and 95 mm at the ends. Both faults are in the middle of the specimen. Fault 1 consists of 9 simulated circular corrosion pits 3 mm deep with diameter of 15 mm on both sides of the specimen (see Figure 1). Fault 2 is a single circular hole with surface diameter of 41 mm and inner diameter of 22mm (see Figure 2). The specimens are made of both old and new steel. The old steel is mild, pre 1890 steel and the new steel is S355. The behavior of the old steel is the main focus of this work and the new steel is used to check the results to exclude the influence of cyclic loads already introduced to the steel.

The FRP reinforcement is applied on both sides of the specimen. The wet layup process is used. The FRP patches are 300 mm long and 60 mm wide. There are 4 layers of heavy 600 g twill woven carbon textile on each side, made of the high strength carbon fibres, supplied by Havel Composity a.s.
They constitute the main reinforcement. One layer of glass textile is added between steel and carbon to prevent the creation of galvanic cell. The epoxy resin is SikaDur 300, supplied by Sika s.r.o.

**Figure 1.** Geometry of specimen with fault type 1  
**Figure 2.** Geometry of specimen with fault type 2.

**Figure 3.** Specimen fault 2 without reinforcement  
**Figure 4.** Specimen fault 2 with reinforcement applied

### 2.2. The experiment set-up

In the test rig the specimen is connected to the fasteners by two prestressed bolts. The fasteners are made up of two parts for easy handling and they connect the specimen to the load cell on one side and to the ground on the other. To measure the stress distribution on the specimen two strain gauges are applied to the side of the specimen. The test rig can be seen on figure 5.

The specimens are loaded with cyclical loading force until the failure. The number of cycles needed is the main parameter measured. During the loading the specimens are always in tension. As mentioned above the force used was established in the numerical study. The magnitude was set to be between 3-66 kN for the specimen without the reinforcement and between 3-85 kN for the reinforced element at the frequency of 5 Hz. The different forces are used to produce similar level of stress inside the steel. The idea behind this was that the specimens will crack roughly at the same time.
3. The results

There are 40 specimens in total. As the experiments started not long ago the results presented here are based on the first tested samples. So far five specimens were tested successfully and one specimen is currently being tested. They all have the fault type 2, the corrosion hole. Even with this number of cases at the beginning of the experiments, the results show increase in the number of cycles the reinforces specimen is able to withstand. Of course more data, that will be available after all 40 specimens are finished, is preferable for making the definite conclusions.

3.1. Specimens without reinforcement

Three specimens without the reinforcement were tested. It was specimens number 9, 11 and 12. In the table 2 you can see the record for each experiment. Originally based on the numerical study the specimen was estimated to last about 250 000 cycles. This was determined using the UIC 778-2 R leaflet. The topic of this leaflet is the determination of remaining fatigue life for existing steel bridges. The adequate permissible stress range for this concrete fatigue prone detail is 85 MPa. Out of this the number of cycles was established using the standard procedure. The area of the damaged cross section is 371 mm$^2$ and the force applied is ca 63 kN, which corresponds to max stress range of 170 MPa. The actual life expectancy during the experiment is however higher, as expected. All three of the specimens reached around 400 000 cycles before breaking. This is mainly due to the probabilistic nature of the S-N curves as they give 5% quantile of breaking. The applied force was modified for each sample. This was based on the real strains measured at the specimen, where optimal strain for all samples was app. 740 microstrains. That is why the specimen no. 9 was loaded only with maximal force of 50 kN. Due to the imperfections this specimen was loaded very asymmetrically.

![Figure 5. The test rig, schema (right) - (1) specimen, (2) the fastener – two parts, (3) prestressed bolts, (4) steel joint, (5) loading cell, and photo (left).](image)

| Specimen No | Total time | cycles | $F_{MIN}$ [kN] | $F_{MAX}$ [kN] | SG. 1[µm/m] | SG. 2[µm/m] |
|-------------|------------|--------|----------------|----------------|-------------|-------------|
| 9           | 23:21      | 420218 | 3.53           | 53.2           | 749         | 329         |
| 11          | 23:18      | 419435 | 3.53           | 66.48          | 765         | 658         |
| 12          | 22:13      | 398959 | 3.53           | 66.52          | 704         | 719         |
3.2. Specimens with reinforcement

There are two reinforced specimens already tested (number 17 and 18). According to the preliminary study the reinforcement should under the same load lower the stress in the steel by one third. This was confirmed by statically loading of the reinforced specimen. From app. 750 microstrains the value measured on the reinforced element sunk to app. 550 microstrains. This reduction should effectively double the life expectancy (see [8]).

In order to test samples in the reasonable time range, a different approach was chosen to test the reinforced specimens. The specimens were loaded not with the same force as before but with force that would produce the same stress in steel. Same stress should mean the same time till the breaking of the steel. The loading force in the range between 3-85 kN was chosen.

| Specimen No | Total time | cycles | $F_{\text{MIN}}$ [kN] | $F_{\text{MAX}}$ [kN] | SG. 1[μm/m] | SG. 2[μm/m] |
|-------------|------------|--------|---------------------|---------------------|-----------|-----------|
| 17          | 17:21      | 312171 | 3,53                | 85,7                | 831       | 639       |
| 18          | 14:50      | 267695 | 3,53                | 85,7                | 744       | 688       |

The breaking of the specimen is still abrupt. The development of the initial crack leads to rise in the measured strains. This continues as the crack grows until the brittle fracture, which is denoted by sharp decrease of measured strain. The crack is now so wide that the remaining steel plasticises and finally breaks completely. The carbon lamella doesn’t show any signs of delamination during this process. It breaks of the steel when the specimen breaks completely. The critical point in this is the shear strength of the epoxy resin.
3.3. Comparison of reinforcement effectiveness

In reality the specimen did not resist to the number of cycles, that were expected. Several reasons can be found, such as the complex stress behaviour in the corrosion pit, usage of older steel with worse material parameters etc. The impact of accumulated load was also verified, but the samples from the old bridge were taken from parts, which should have not been influenced by it.

To compare the two sets, we have to calculate the number of cycles that would occur if the stress range corresponds to that of unreinforced specimen. To do this we have to establish proper S-N curve for the reinforced detail. To do this we used Eurocode 1993-1-9 section 7.1. Out of the equation:

\[ \Delta \sigma_R^m \cdot N_R = \Delta \sigma_C^m \cdot 2 \cdot 10^6, m = 3 \text{ for } N \leq 5 \cdot 10^6 \]  

(1),

where we know the number of cycles \( N \) (300 000 app. the mean value) and the real stress range \( \Delta \sigma_R \) (221 MPa in the steel without calculating the influence of ideal cross-section). From here we can calculate the fatigue prone detail to have fatigue limit at 117 MPa with \( 2 \cdot 10^6 \) cycles. Then we use this value again in the same equation (1) to calculate the number of cycles needed while using the stress range of the unreinforced specimen (170 MPa).

\[ 170^3 \cdot N_R = 117^3 \cdot 2 \cdot 10^6 \rightarrow N_R = 651 990 \text{ cycle} \]  

(1.1),

If we would be using the same force for the reinforced element as was used for the unreinforced one, we should expect the failure after approximately 650 000 cycles. The life expectancy will grow only 1.6 times and not the predicted 2 times. However, this is still quite substantial rise.

4. Conclusions

The carbon fibre reinforcement is shaping to be a viable option for strengthening of old steel structures. As was shown in this article the reinforcement can increase the life expectancy of such structures. Furthermore, the materials are very easy to handle and they are quite versatile to use. And also in terms of costs the carbon reinforcement available is reasonably cheap.

On the other hand, these assumptions are based only on the experiments that have happened so far. To make the final conclusions on effectiveness more data is needed and we have to wait to finish all of planned experiments. The method used to strengthen the specimens has also some drawbacks. As it is a hand layout the quality of the reinforcement depends heavily on the person doing it. It does not prevent cancelation of traffic. In order to activate the reinforcement, there can’t be any load applied. This can be however remedied by prestressing the reinforcement.

Acknowledgements

Research in this paper was supported by COST CZ (LD) project of the Ministry of Education, youth and sports LD (No. LD15131) “Fatigue behaviour of FRP reinforced steel members under severe environment”.

References

[1] Macho M and Ryjáček P 2016 Proc. Int. Conf. on Engineering Sciences and Technologies ESaT 2015 123-28
[2] Colombi P, Bassetti A and Nussbaumer A 2003 Fatigue Fract. Eng. Mater. Struct. 26 569-66
[3] Tavakkolizadeh M and Saadatmanesh H 2003 Feb J. Struct. Eng. 186-96
[4] Tavakkolizadeh M and Saadatmanesh H 2001 J. Compos. Constr. 5 200-10
[5] Pipinato A, Pellegrino C and Modena C 2012 Mod. App. Sci. 6 no 10
[6] Xiao-Ling Zhao X and Zhang L 2007 Eng. Struct. 29 1808-23
[7] CNR Italian Advisory Committee on Technical Recommendations for Construction 2005 Guide for the design and construction of externally bonded FRP systems for strengthening existing structures. FRP systems for strengthening existing structures
[8] Vůjtěch J, Ryjáček P and Vovesný M 2016 Proc.2nd Int. Conf. on Engineering Sciences and Technologies ESaT 2016 art. no 126