The residual lifetime of steel bridges under the action of fatigue and corrosion effects.

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Abstract. Decades-old steel bridges have to face the unfavourable environment that causes the ageing and deterioration of material properties. Moreover, especially railway bridges, which are famous for permanent resistance to heavy movable load, are exposed to large number of stress ranges that may lead to fatigue damage. Combination of both phenomenon has significant impact on the condition of bridges and their remaining service life. The subject of the proposed paper is observation the response of steel bridge structures containing construction elements weakened by corrosion on cyclic load. For the purpose, the series of laboratory fatigue tests were performed on samples of riveted connections. Specimens with various level of corrosion weakening had been taken from historical railway bridge and were loaded by cycling force in tension subsequently. The laboratory tests were supported by numerical analysis. This paper presents knowledges gained from the study that was focused on how to take into account the combined effect of degradation process and fatigue. The evaluation of the tests indicates that the service life of members may be significantly reduced due to fatigue. The developed relationship between corrosion loss and reduced detail category is stated.

1. Introduction
Metallic bridge structures built many decades ago represent historical and cultural significant structures. Nevertheless increasing demands on transportation in combination with unfavourable environment have negative effects especially on the state of existing railway steel bridges. Civil engineers reassessing such existing structures face several sources of doubt, especially if the structure is deteriorated by a combination of corrosion and fatigue load.

The effects of corrosion weakening on the behaviour of steel elements has been the subject of many research projects. A set of corroded steel riveted stringers was subjected to laboratory tests to find the influence of material loss on the remaining bearing capacity of these bridge structure elements [1], [2]. In several cases [3], [4], the influence of corrosion on the fatigue behaviour of corroded steel plates was investigated. The origin and propagation of fatigue cracks on corroded elements were also studied [5]. The response to cyclic loading of steel webs and flanges with material loss due to corrosion was the topic of another study [6]. In the case of riveted connections, the effect of rivet head corrosion on the pre-stressing of the rivet was investigated by laboratory tests and numerical simulations [7]. From the point of view of fatigue, the shear category of rivets for riveted shear splices is considered to be category 100, which is equivalent to splices jointed with non-preloaded bolts [8].
The studies mentioned above were based largely on the behaviour of simple steel plates. The research presented in our paper focuses on elements taken from real structures that had been in service for more than 100 years. The experimental tests performed on these samples best depict the behaviour of the kinds of structures that civil engineers usually meet with. Moreover, the material loss of all tested samples is a result of the natural corrosion process, so the shape of the corroded surface and the irregularities fully corresponds to reality.

The paper presents observations from laboratory tests of riveted bridge components and remaining fatigue life, in the presence of natural corrosion weakening at various levels and with various distributions.

2. Laboratory tests on fatigue
Tested specimens for fatigue tests were taken from the bottom flange of the truss girder of the old railway bridge in Holubov (see Fig. 1). The samples were chosen to focus on details susceptible to fatigue and, at the same time, to focus on parts that will be deteriorated by corrosion. In addition, the samples were chosen from parts where the impact of the cumulated damage is negligible or below the limit of the permanent fatigue life. The aim of the experimental tests was to find how the remaining fatigue life of the steel bridge components is affected by various levels of corrosion weakening.

2.1. Bridge description
The Holubov bridge is a steel truss riveted railway bridge with an upper deck that was built in 1892 (see Fig. 1). From the static point of view, the structure acts as a continuous beam with 2 spans (2x41.9=83.30 m). As was mentioned above, this structure was chosen because of its age and because there was significant corrosion damage. In addition, the bridge was under reconstruction.

![Figure 1. Holubov Bridge.](image)

2.2. Tested samples
All specimens for laboratory tests were cut from the bottom flange of the riveted truss girder. The most significant corrosion weakening was found on the flange angles connecting the flange to the web. For this reason, the riveted joints of the sheets forming the bottom flange with the angle mentioned above were chosen as the experimental specimens (see Fig. 2). The samples were cut manually by a band saw. The final precise shape was done by milling. Due to this procedure, the temperature influence of samples was avoided.

![Figure 2. Tested sample (photo).](image)
The size of the tested samples is based on the geometry of flange angle L100x100x12 and position of rivets. Each specimen consists of 4 steel sheets 12+9+9+8 mm in thickness, which are connected by 3 rivets with a shank diameter of 20 mm. The number of 3 rivets was selected with respect to adequate total length of specimen. The axial distance between rivets is 116,5 mm, and the total length of the tested specimen is 626 mm. The width of the specimens is variable, and changes from 80 mm at both ends to 60 mm in the middle of the span. The total number of specimens was 13. All tested samples were divided into 4 groups on the basis of the corrosion level of the upper sheet. The corrosion level was determined as the change in cross-section area due to uniform corrosion in the place of the first rivet, and can be determined according to Eq. (1):

\[
d_A = \frac{\Delta A}{A_0} = \frac{A_0 - A_1}{A_0} [-]
\]

- where: \(A_0\) is the cross-section area of the original uncorroded sheet in the position of the 1st rivet; \(A_1\) is the cross-section area of the corroded sheet in the position of the 1st rivet.

The general characteristics of each group are as follows:

- 1st group: Without corrosion - samples: S1.1, S1.2, S1.3, S1.4
  - characteristics: no measurable corrosion weakening, a change in surface colour only;

- 2nd group: Medium level of corrosion - samples: S2.1, S2.2, S2.3
  - characteristics: a medium level of corrosion loss - especially the upper sheet and the heads of the rivets on the upper surface, medium deep (0.5-1.5 mm) corrosion pits on the upper sheet; a range of corrosion thickness loss of about 1-2 mm;

- 3rd group: High level of corrosion - samples: S3.1, S3.2, S3.3
  - characteristics: a high level of corrosion loss - especially the upper sheet and the heads of the rivets on the upper surface, deep corrosion pits (2-3 mm) on the upper sheet; a range of corrosion thickness loss from about 2-4 mm;

- 4th group: Samples with missing rivet - samples: S4.1, S4.2, S4.3
  - characteristics: no measurable corrosion weakening, a change in surface colour only, the middle rivet is missing.

All tested specimens were sandblasted to remove the corrosion layer before installing the measurement devices. The corroded surface of samples was sandblasted to the smoothness Sa2,5 by the very fine siliceous sand. In order to prevent any impact on the fatigue behaviour, the very fine siliceous sand instead of traditional steel balls was used with the small jet device. The sandblasting of surface was necessary to do because of the installation of strain gauges and to measure the real geometry and observe the cracks on the surface. Subsequently, the photogrammetry method with sufficient accuracy ± 0,5 mm was performed to obtain a 3D model and to find the exact geometry, including corrosion pits, rivet damage and other irregularities. The depth of the corrosion pits was in the range of 0,5 – 1,5 mm, and for the samples with the highest level of corrosion, the depth reached a maximum value of 2 – 3 mm.

A preliminary numerical models of tested specimens have been created to see the behaviour of samples and find out the optimal values of loading force (see Fig. 3). Models were created in Dlubal RFEM software. All plates were modelled as 3D solid members, except fixing device.

A total of 8 small samples were taken from the bottom flange of the truss girder to find the material properties of the steel. According to the results, the material of the bridge components is a mild steel with an average yield strength value of 263 MPa and an average modulus of elasticity value of 207,8 GPa.
2.3. Indicators measured during the tests
All tested samples were divided into two groups. The first group of experimental specimens contained 2 samples that were equipped with a larger number of measurement devices. A total of 10 strain gauges were arranged on each of them to measure the relative strain during the fatigue tests (Fig. 4). The measured data will help to verify the numerical models of the tested samples. Each of these tested specimens was also equipped with a couple of displacement sensors, which measured the movement of individual sheets.

HBM strain gauges were used (1-LY11-1.5/120, 1-LY11-10/120) together with displacement inductive sensors (LVDT) Micro Epsilon of type DTA-10C-CA with nominal displacement ± 5 mm.

All the other specimens were categorized as 2nd phase samples. Unlike the previous group, in this case just 2 strain gauges were installed in the middle of the gap between rivets on the bottom and upper side of the sample (S1+S2). The number and the position of the displacement sensors correspond fully to the previous case.

2.4. Process of the fatigue tests
The tested construction detail was considered to be a bending detail category 71 [9]. The tested sample simulated the connection of the truss members, for example: the connection of the bracing diagonal and the main girder, or the connection of the diagonal and the web of the flange of the truss riveted girder.
Due to unsymmetrical specimen there was a small effect of bending moment that caused additional normal stresses. However, the shape of testes samples was chosen to minimize this effect of bending moment. For this reason the bottom plate was shorter. Also the fixing of samples was designed to minimize the additional stresses caused by bending. As the result, the whole cross-section of sample is loaded by tensile stresses.

It was assumed that a crack occurs on the upper single sheet in the cross-section containing a hole for a rivet. The fatigue test was considered to be ended when:

1. a fatigue crack initiated and had grown to the critical length – in our case, the critical length was considered to have been reached at the moment when the tested sample failed,
2. there was a large displacement (found by the displacement sensors), or
3. when the rivet was damaged.

The values of measured data (relative strain and displacement) were observed continuously in a real time and recorded in period of each 10000 cycles in the phase before the crack initiation and then continuously until the collapse of sample occurred. The frequency of record was set to 100 Hz. Type of the measuring device was Dewetron Dewe 5000.

A special device was manufactured for fixing the samples during the experimental fatigue test (see Fig. 5).

Figure 5. Arrangement of the fatigue test.  
Figure 6. Fatigue damage to tested sample.

2.5. Evaluation of the tests

The values of the stress range were almost the same for all samples - nearly 180 MPa. The assumption of the bending detail category for an uncorroded tested sample was 71 MPa, which corresponds to 123000 cycles for stress range 180 MPa. The measured number of cycles was higher for uncorroded samples, and the ratio of measured-to-expected was equal to 1,5-2,0. The number of cycles for samples with a medium level of corrosion and with a high level of corrosion was also variable, but was generally lower. The ratio for medium level was: 1,3-1,8, and for high level the ratio was: 0,5-1,5.

The failure mode of the tested samples was as had been assumed. The first crack in all cases occurred in place of hole for the first rivet, in weakened cross-section area. The crack propagation was in direction perpendicular to main stresses. The samples became damaged after the crack reached its critical length.
and the weakened cross-section was not able to transfer the loading force. An example of a damaged specimen is shown in Fig. 6.

Figure 7 summarizes the number of cycles that were needed for the initiation of a crack, the number of cycles after which damage to the samples occurred, and the number of cycles that were necessary for crack growth. Each column shows the average number of cycles for one set of specimens (1 – samples without corrosion, 2 – samples with a medium level of corrosion and 3 - samples with a high level of corrosion). It can be seen that there is a downward tendency in the number of cycles for crack initiation. The number of cycles for crack initiation decreases slightly with the increase in corrosion weakening. However, this effect is not so evident for individual samples, because of the fluctuation in the numbers in each set. Because of the small dimensions of tested samples, the number of cycles for crack initiation prevails over the number of cycles for crack growth.

Figure 7. Number of cycles for crack initiation and crack growth.

This type of laboratory test was performed mainly to find out whether or not there is any change in the bending detail category when there is corrosion weakening. In most cases, corrosion weakening consists of a uniform part and an irregular part. The irregular part means a locally increased depth of corrosion in the form of corrosion pits. The results of the test are shown in Fig. 8 in the form of the relationship between the number of cycles and the set of specimens. There is a downward trend in number of cycles, accompanied by an increasing level of corrosion.

Figure 8. Dependence of the number of cycles on the level of corrosion.

| No. | Sample | Cycles Ni | Bending detail category $\Delta\sigma_{c,R}$ [MPa] |
|-----|--------|-----------|-----------------------------------------------|
| 1   | S1.1   | 184452    | 79.2                                          |
| 2   | S1.2   | 251053    | 84.5                                          |
| 3   | S1.3   | 186320    | 77.7                                          |
| 4   | S1.4   | 300140    | 89.6                                          |
| 5   | S2.1   | 179633    | 77.7                                          |
| 6   | S2.2   | 161769    | 75.4                                          |
| 7   | S2.3   | 222551    | 83.6                                          |
| 8   | S3.1   | 139313    | 70.9                                          |
| 9   | S3.2   | 62003     | 55.6                                          |
| 10  | S3.3   | 182980    | 77.3                                          |
| 11  | S4.1   | 104000    | 62.0                                          |
| 12  | S4.2   | 171843    | 72.5                                          |
| 13  | S4.3   | 313553    | 94.5                                          |
The measured number of cycles until the failure was higher than the assumed number, which means that the real bending detail category must also be higher. The real parameters (geometry, load) were therefore considered for a calculation of the real bending detail category of the tested riveted joint (see Table 1). Detail category was based on the number of cycles that corresponded to total failure of the sample. In this case, too, a downward tendency can be observed – the higher the corrosion loss, the lower the bending detail category, in terms of average values. The evaluation was based on the fatigue curve taken according to [9].

Neglecting tested sample S3.2, the bending detail category value of which was deviated most from the other values, and using regression analysis, the dependence between the category of the detail and the change in cross-section area can be expressed by a linear relation as (2) and (3) (see also Fig. 9):

\[ \Delta \sigma_{c,R} = \Delta \sigma_c \cdot c_R \quad [\text{MPa}] \]  
\[ c_R = (1 - 0,4874 \cdot d_A) \quad [-] \]

- where: \( \Delta \sigma_{c,R} \) is the reduced bending detail category; \( \Delta \sigma_c \) is the original bending detail category of an uncorroded sample; \( d_A \) is the level of corrosion determined as the change in cross-section area for members loaded by axial force. In case of members loaded by bending moment or loaded by combination of bending moment and axial force, the level of corrosion is considered as change in cross-section area of assessed part of member.

Coefficient \( d_A \) takes into account the change in the cross-section area as a consequence of the uniform part of the corrosion. The influence of irregularities of the corroded surface are not included in this calculation. However, the authors are currently working on this issue, and the effects will be stated in a later stage of our investigations. Surface irregularities may have negative effects on the course and the distribution of the stresses in a member. If the corroded surface is rough, the influence of irregularities is higher than in case of smooth surface. Then the initiation of fatigue crack might become earlier, after lower number of cycles.

Since the stated formulas are derived from the experimental tests introduced above, their applicability is limited to narrow members, i.e. to steel plates not more than 60 mm in thickness.

![Figure 9. Relation between bending detail category and level of corrosion weakening.](image-url)

To find out the accuracy of the formula that has been developed, the Root Mean Square Error (RMSE) was used to calculate how much error there is between the predicted values and the observed values. For the bending detail category the RMSE = 0.527 [-]. This error is due to the dispersion of the results from the experimental test, together with the fact that the combined effects of corrosion and fatigue phenomena are very complex. The value is therefore acceptable.
3. Conclusions

Laboratory tests on real steel bridge components led to several significant conclusions:

The bending detail category of tested samples without corrosion weakening corresponds to category 75 MPa in the 95% quantile. This means that the assumption of use category detail 71 was on the safe side. In terms of the number of cycles, the measured number is 1.5 to 2 times higher than the number expected for category 71.

Degradation in the form of corrosion has a negative impact on the fatigue behaviour of steel members. The irregularities of the corroded surface cause changes in the stress distribution. Fatigue cracks generally occur earlier, and the fatigue life is shorter for the same value of the nominal normal stress, in comparison with uncorroded elements.

The change in the length of the fatigue life can be described by the change in the fatigue curve in dependence on the corrosion level. The relation between the bending detail category and the corrosion loss may be expressed by a linear function, and the new detail category for narrow members can be calculated using reduction coefficient $c_R$. However, it is not always the rule that the higher the level of corrosion, the lower the fatigue life. The roughness of the degraded surface also plays an important role, but is not included in the $c_R$ factor.

If the corrosion phenomena investigated here are not taken into account when evaluating the current and future state of existing structures, their remaining lifetime may be overestimated.

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