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FATIGUE TESTING OF A BOLTED CONNECTION FOR BURIED FLEXIBLE STEEL CULVERTS[1]

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A fatigue assessment of steel structures based on the safe life approach requires a detail category representing the fatigue strength. For flexible culverts there are no matching details in the governing regulations. In this paper the testing and evaluation of the fatigue strength of a standardized bolted connection for steel culverts are presented. A test rig was designed to mimic the in-service conditions with a combination of bending moment and axial force. A total of ten specimens was tested to failure. The failure was governed cracks initiating at the indentations from the bolt heads and propagated towards the nearest edge. From the test results, an *S-N* curve has been derived suggesting a characteristic fatigue strength of 124 MPa at 2 million cycles and a slope of 5 in log-log scale.

Key words: Fatigue, Testing, Bolted connection, Culvert.

1. INTRODUCTION

The structural behaviour of a soil–steel composite bridge is by definition governed by the interaction between the steel plates and the surrounding soil. If the structure is loaded with traffic, the stress variation in the steel plates and especially at the connections might lead to the initiation and propagation of fatigue cracks. The load effect is the result of a rather complex interaction between the steel plates and the soil, while the fatigue deterioration is a local phenomenon occurring at details with high stress concentrations. A conventional fatigue assessment following standards, such as the Eurocode, is based on the safe life method and a fatigue strength defined by a detail category. For bolted connections of corrugated steel plates, no perfectly matching detail category is available.

This paper is focused on the fatigue strength of a specific bolted connection frequently used in soil–steel composite bridges. Fatigue tests have been made with a setup to ensure a realistic behaviour of the connection subjected to a combination of bending moment and axial force. The joint is shown in Figure 1. Idealizing this joint to a one sided beam connection would, according to the

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Eurocode EN 1993-1-9 [3], give a detail category of 90 or 50 with preloaded high strength bolts or non-preloaded bolts, respectively. The detail category corresponds to the fatigue strength at 2 million cycles. The applicability of this connection can, however, be questioned since it is based on tests on beams with symmetric I-shaped cross-sections, quite different in shape and behaviour from bolted corrugated plates.

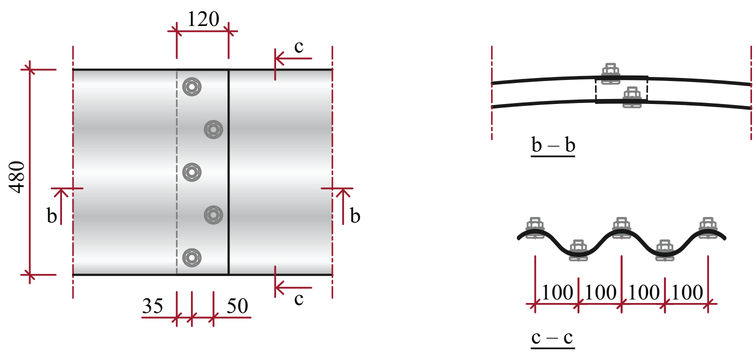

Figure 1. The tested bolted connection. All dimensions are given in millimetres

Only a few fatigue tests on bolted connections of corrugated plates can be found in the literature. One example is the test reported in [9] which comprised 18 specimens and numerical simulations. The study was focused on the assemblage of the connection and its influence on the fatigue life. Half of the specimens where assembled following the governing practice and resulted in a fatigue detail category of 90. A faulty assemblage resulted in considerable lower fatigue strength. This malfunctioning is avoided in practice today by the use of standardized hole configurations and tapered bolts. Results from the same test are presented also in [10]. Another test is presented in [6] where a detail category between 80 and 90 is suggested. The conditions and design were, however, quite different in comparison to the test presented in the current paper. The bolts and nuts had different properties and the specimen was loaded in pure bending.

A method for design against fatigue can be found in [13] including a procedure to calculate the load effect. The overall aim of the tests conducted and presented in this paper is to arrive at an adequate detail category for fatigue assessment that can be used in the design process. The scientific contribution is the test results presented and an increased understanding on the behaviour of this type of connection subjected to cyclic loading.

The paper has the following outline. A description of the testing conditions is given in Sec. 2. The method for the statistical evaluation is presented in Sec. 3. In Sec. 4 numerical results and failure modes are presented. The paper is ended with conclusions in Sec. 5.

2. TESTING CONDITIONS

The experimental setup was designed to mimic the real behaviour of a bolted connection in a soil–steel composite bridge. The thickness and radius of the specimen was the same as for the real bridge built in Enköping, Sweden [12]. A sketch of the specimen and the frame is shown in Figure 2. The main plates had a length of 1.06 m, a width of 0.48 m, and a thickness of 3 mm. They were cold formed to a curved shape with a radius 3.052 m as indicated in the figure. The plates were bolted to the frame and to each other. The specimen was subjected to four points bending with the crucial connection located in the middle.

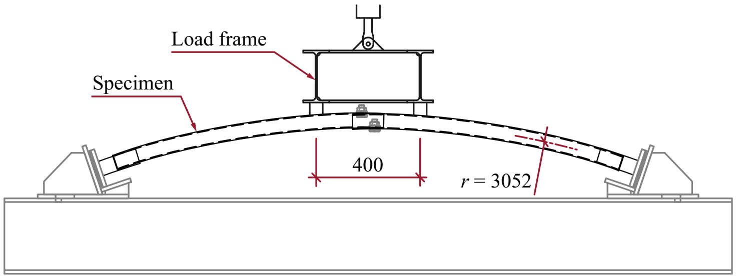

Figure 2. A sketch of the experimental setup. All dimensions are given in millimetres

To attain a realistic combination of bending moment and axial force at the bolted connection, the supports where designed with tangential elastic springs and a hinge to allow rotations. A sketch and a photo of the support are shown in Figure 3. The intention was to reach a zero bending moment at the supports but this was not completely fulfilled. It is evident from the results that some restraining was present.

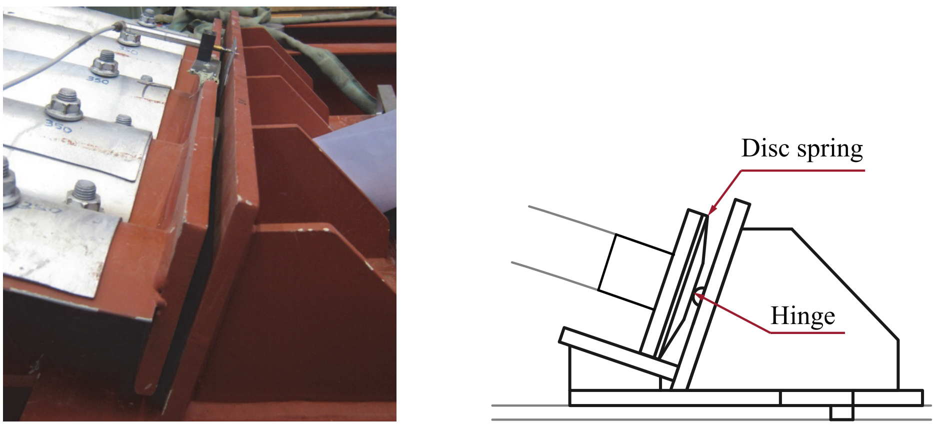

Figure 3. The support structure of the specimen

A more detailed description of the experimental setup can be found in [7] and [8].

2.1. Material

The steel plates of the specimens had a cross-section corresponding to the trademark MultiPlate MP 200 profile [14] with a thickness of 3 mm and a corrugation height of 55 mm, see Figure 1. The bolted connection was composed of five bolts, three at the crests and two at the valleys. The bolts with class 8.8 and diameter of 20 mm had oval-shaped heads, with cams fixing the heads to the plates to facilitate mounting. The bolts where preloaded with a torque moment of 350 Nm. A photo of a bolt after testing can be seen in Figure 8.

Material samples from plates of the same batch as the fatigue specimens were tested and classified as S355MC according to EN 10149-2 [2]. A summary of the chemical composition of five samples is given in Table 1. These five samples are not directly associated to the ten fatigue specimens but are representative for the material used.

Table 1. Chemical composition in percent of the steel in the specimens

Sample	C	Si	Mn	P	S	Al	Nb	V
1	0.056	0.01	0.71	0.007	0.006	0.033	0.029	0.008
2	0.056	0.01	0.71	0.008	0.005	0.031	0.027	0.010
3	0.055	0.02	0.81	0.009	0.003	0.041	0.029	0.005
4	0.054	0.01	0.82	0.008	0.004	0.020	0.023	0.007
5	0.055	0.02	0.81	0.009	0.003	0.041	0.029	0.005

2.1. Loading

The loading was applied by a hydraulic jack above the specimen and the load frame as indicated in Figure 2. This load where then divided between two load lines, each at a distance of 200 mm from the crown. Along the lines, adjustable steel teeth transmitted the force from the load frame to the corrugated specimen. The maximum load varied between 30 kN and 50 kN depending on the desired stress range. The frequency of the load variation was set to 1 Hz.

During one of the first tests a crack was initiated by the contact pressure at one of the teeth before any sign of cracks at the bolted connection appeared. In the subsequent tests, a protecting plate and a layer of neoprene were placed between the steel teeth and the specimen to avoid the concentrated contact pressure. A photo of one of the load lines is shown in Figure 4.

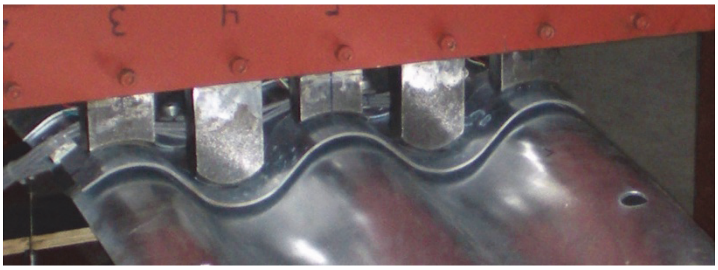

Figure 4. The adjustable teeth for loading the specimen and the protecting plate

2.2. Instrumentation

To record the behaviour of the specimen during testing a monitoring system consisting of several types of sensors was used. The applied force was measured using a load cell and a displacement gauge at the connection between the hydraulic jack and the load frame. The deformation of the specimen was measured using displacement gauges of type LVDT distributed over the surface. Strain gauges were distributed over the specimen to record the strains in the plates. The locations of the sensors were in principle the same for all specimens as it is shown in Figure 5.

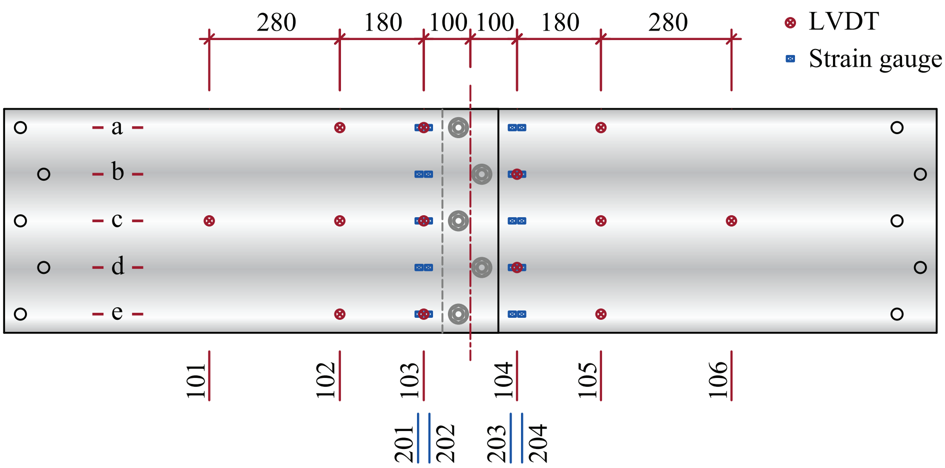

Figure 5. A schematic view of the instrumentation of the specimens. The displacement gauges (LVDT) were numbered 101 to 106. The strain gauges were numbered 201 to 204. The transversal location was indicated by the letters a to d

Alterations were made to the sensor setup for some specimens to investigate specific issues in the behaviour but these are not treated herein. A more detailed description of the instrumentation can be found in [8].

3. STATISTICAL EVALUATION

The fatigue resistance can be described by the well-known Basquin relation [1]

$$N = K\, S_{\mathrm{r}}^{-m} \tag{1}$$

where K and m are coefficients describing the linear relation in log-log scale between the number of cycles N and the stress range S_{r}. These coefficients are often determined by regression analysis based on the method of linear least squares [4]. However, this method does not allow a consideration of censored data, so-called runouts. The statistical analyses presented herein have, therefore, been performed using the maximum likelihood (ML) method instead, which allows a consideration of censored data [11]. A fundamental assumption is that $\log_{10}(N)$ is normal distributed.

During the test, it was not possible to maintain the stress range perfectly constant. Hence, the evaluation of the fatigue resistance was performed using the Palmgren–Miner rule which together with (1) can be formulated as

$$D = \sum_i \frac{n_i}{N_{\mathrm{R}i}} = \sum_i \frac{n_i\, S_{\mathrm{r}i}^m}{K} = \frac{1}{K} \sum_i n_i\, S_{\mathrm{r}i}^m \tag{2}$$

where D is the accumulated damage and n_i is the number of cycles in stress range $S_{\mathrm{r}i}$. With the condition that the accumulated damage is unity when the fatigue life is exhausted, the stochastic variable K can be expressed as

$$K = \sum_i n_i\, S_{\mathrm{r}i}^m \tag{3}$$

The number of cycles n_i and the stress ranges $S_{\mathrm{r}i}$ are the result of the tests. The mean value and the standard deviation for K have been determined using the ML method. The variable m has been treated as a constant determined by minimizing the standard deviation for K.

The mean fatigue endurance is described by the Basquin relation, the mean value for K and the constant m. For design purposes, a characteristic fatigue endurance has to be determined which can be defined by the 5 percent fractile of K with a consideration of the number of specimens as [5]

$$\log K_{\mathrm{c}} = \overline{\log K} - s_{\log K}\, t_p \sqrt{1 + 1/n} \tag{4}$$

where K_{c} is the characteristic value, $\overline{\log K}$ is the estimated mean value, $s_{\log K}$ is the estimated standard deviation, and t_p is the fractile for the Student's *t* distribution with $n - 1$ degrees of freedom where n is the number of specimens. In the current case with $n = 10$ and $t_{0.95} = 1.83$, equation (4) can be simplified to

$$\log K_{\mathrm{c}} = \overline{\log K} - 1.92\, s_{\log K}$$

4. RESULTS

The assessment of the fatigue resistance during the design stage is typically based on nominal stresses in the plates [13]. To attain the corresponding reference stress from the tests, a theoretical model was created with a statical system as shown in Figure 6.

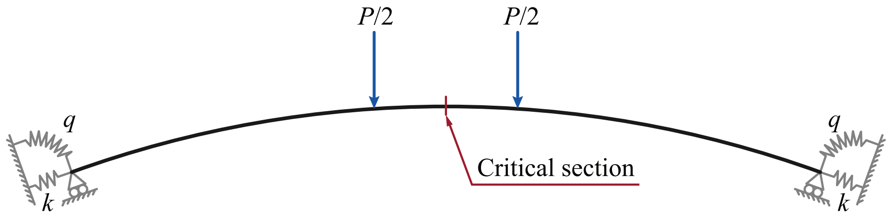

Figure 6. The statical system of the theoretical model. The variables k and q correspond to the tangential and rotational stiffnesses, respectively.

The structure is statically indeterminate and the stiffnesses at the boundaries (k and q in Figure 6) have a strong influence on the stresses at the critical section. These stiffnesses are difficult to determine with accuracy due to uncertainties as friction and misalignments at the supports. By fitting the response of the theoretical model to the measured displacements of the specimens, these uncertainties were circumvented and the nominal stress could be determined with acceptable accuracy. The results of the tests are summarized in Table 2 as the mean nominal stress range and number of cycles to failure.

Table 2. Mean nominal stress range and the number of cycles to failure for the ten specimens

Specimen	**E[S_r]/MPa**	N_{tot}	**Notes**
1	157	4 197 000	
2	199	164 100	Runout
3	189	343 800	
4	217	324 000	
5	112	9 767 000	Runout
6	173	765 000	
7	166	772 200	
8	163	1 773 000	
9	180	576 000	
10	135	2 129 000	

Specimen 2 in Table 2 was treated as a runout because a fatigue crack appeared at a local indentation along the load line, not at the bolted connection. For the following specimens, a protecting layer was implemented as shown in Figure 4.

The failure of the specimen was defined as the instant when a distinct change was detectable in the measured response. Daily visual inspections were performed and when a crack was detected, the measured response was thoroughly investigated. The actual number of cycles to failure was typically identified based on a combination of changes in stiffness ratios, stress ranges and displacements. The procedure is thoroughly explained in [8].

Typical crack patterns at failure are shown in Figure 7. The cracks initiated at the rims of the bolt holes and propagated towards the nearest edge. The indentations caused by the cams on the bold heads seem to be the cause of the initiation.

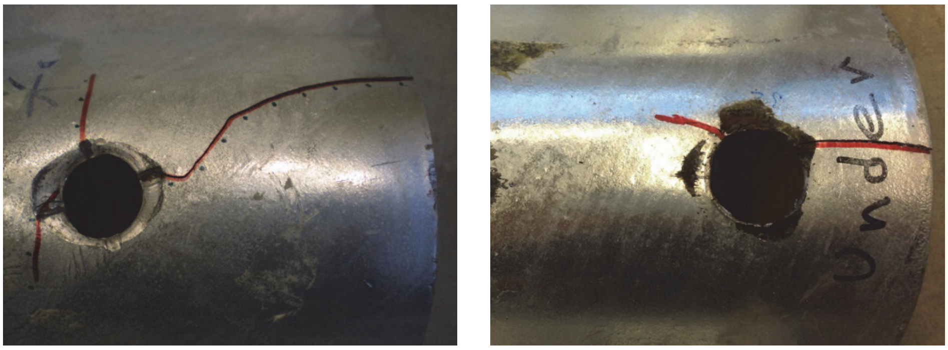

Figure 7. Crack patterns for specimen 1 and 6, respectively.

None of the specimens failed by fractures in the bolts. Minor defects and wear could be seen on the bolts after dismantling, see Figure 8, but no severe damage.

Figure 8. A bolt and nut after dismantling

The result of the statistical evaluation is shown in Figure 9. Two alternatives are shown, one with an m value determined to minimize the standard deviation of K, and another with $m = 5$ in compliance with one of the values suggested in the Eurocode.

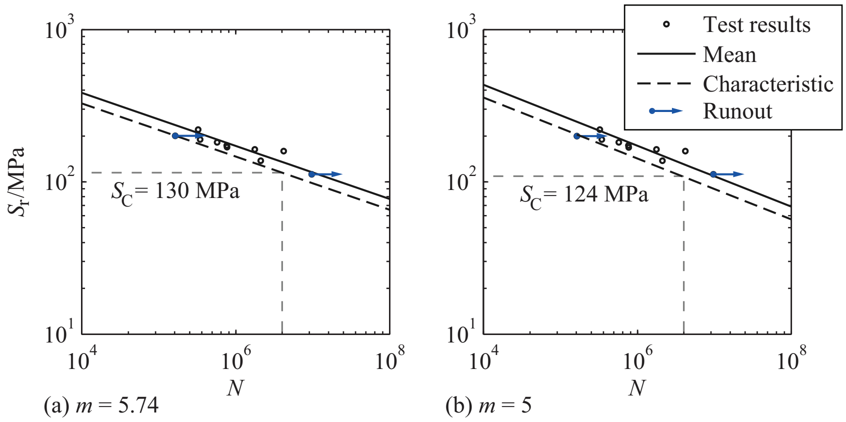

Figure 9. The derived *S–N* curves for m = 5.74 (a) and m = 5 (b).

The evaluation considering a non-fixed m value gives a characteristic fatigue strength of 130 MPa at 2 million cycles, see Figure 9(a), which is valid for $m = 5.74$. The associated standard deviation for $\log_{10} K$ was determined to 0.21. Setting the m value to 5 gives a fatigue strength of 124 MPa, see Figure 9(b), and a somewhat larger standard deviation of 0.22.

The derived fatigue strength is higher than suggested in [9] and [6], where the corresponding values range from 80 to 90 MPa. There are, however, differences in the design of the bolted connections and the experimental setup which are the probable causes of the differences. The tests presented herein have been performed with a setup designed to mimic field conditions and, with a bolted connection in compliance with the specification in [14].

5. CONCLUSIONS

The following conclusions are based on the fatigue testing of the specific bolted connection shown in Figure 1, designed in compliance with the instructions in [14].

- Based on ten tested specimens, a characteristic fatigue strength of 124 MPa at 2 million cycles have been derived.
- An inclination of $m = 5.74$ gives the best fit of the *S–N* curve to the data. However, a fixed value of $m = 5$ gives only a minor difference in dispersion and characteristic value.

– The fatigue cracks initiated at the indentations from the cams of the bolt heads, and propagated towards the nearest edge.

To establish the value suggested for the fatigue resistance, more tests should be performed for specimens with different design and dimensions. Looking at the whole fatigue design procedure, efforts should also be put on investigating stress levels during service conditions.

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