

Fatigue Tests of New Assembly Bolt Connections for Perspective Temporary Steel Railway Bridges

Marcela Karmazínová, Michal Štrba, Milan Pilgr

Abstract—The paper deals with the problems of the actual behavior, failure mechanism and load-carrying capacity of the special bolt connection developed and intended for the assembly connections of truss main girders of perspective railway temporary steel bridges. Within the framework of this problem solution, several types of structural details of assembly joints have been considered as the conceptual structural design. Based on the preliminary evaluation of advantages or disadvantages of these ones, in principle two basic structural configurations – so-called “tooth” and “splice-plate” connections have been selected for the subsequent detailed investigation. This investigation is mainly based on the experimental verification of the actual behavior, strain and failure mechanism and corresponding strength of the connection, and on its numerical modeling using FEM. This paper is focused only on the cyclic loading (fatigue) tests results of “splice-plate” connections and their evaluation, which have already been finished. Simultaneously with the fatigue tests, the static loading tests have been realized too, but these ones, as well as FEM numerical modeling, are not the subject of this paper.

Keywords—Bolt assembly connection, Cyclic loading, Failure mechanisms, Fatigue strength, Steel structure, Structural detail category, Temporary railway bridge.

I. INTRODUCTION

THE grant project titled “Research of necessary operating parameters of perspective railway steel temporary bridges” has been solved on the authors’ workplace recently. Within the framework of this research project, one of the important and significant problems is to develop and verify the new type of the bolt assembly connection. The connection has to comply with the set of requirements, not only the simple and fast assembly, but also the wear hardness or the possibility of the replacement of the parts worn with use, as well as the reliability in the ultimate limit states and serviceability limit states, including structural reliability in case of fatigue effects.

To describe and verify the actual behavior of a new bolt assembly connection in the loading process of the real structure, the static loading tests [1], [4], as well as the fatigue loading tests, including the subsequent elaboration and

evaluation of monitored and measured significant strength quantities, have been realized.

II. TEST SPECIMENS

A. Principle of Investigated Assembly Connection

The mentioned type of the assembly connection, which has been investigated, consists of two end steel plates forming a single unit together with connected member. Both connecting plates have a pair of narrow opposite flanges and three holes for bolts. The connection also has two splice plates, likewise with narrow flanges and corresponding number of the bolt holes, and six fastening bolts. The behavior is based on the principle, that at first the tensile force is transferred from one member to the splice plates by mutually lock of their flanges, and then by splice plates through the gap between end plates to the member on the opposite side of the connection. Fastening bolts prevent the opening or separating of splice plates. The principle scheme of investigated so-called “splice-plate” connection is drawn in Fig. 1, including its detailed configuration and dimensions.

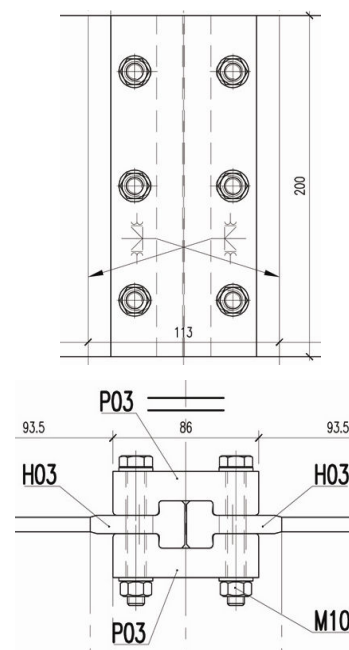


Fig. 1 “Splice-plate” connection: principle scheme

The geometrical parameters of “splice-plate” connection are as follows: the thickness of splice plates is 12 mm and the thickness of end plates is 10 mm.

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B. Configuration of Test Specimens

The configuration and dimensions of created connection has been taken as a base for the shape and geometry of the test specimens, which have been experimentally verified, when subjected to the cyclic loading effects. The resulting length of the test specimen was about 700 mm and the width was 200 mm in its middle part, while the width on the ends has been decreased about to a half, i.e. 100 mm, because of fixing in the testing equipment. The scheme of the whole test specimen is seen in Fig. 2.

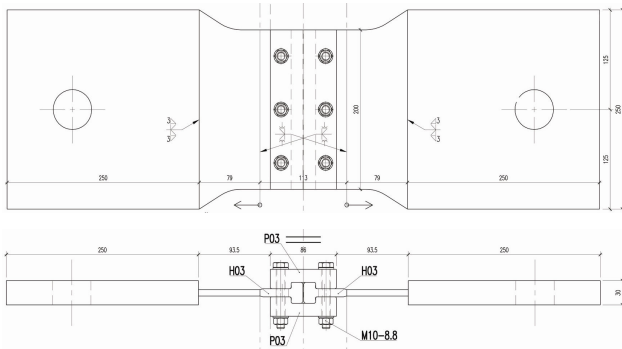


Fig. 2 "Splice-plate" connection: scheme of test specimen

The material used for the considered assembly connection is steel of S 235 grade. The real shape, configuration and dimensions of the test specimen, as it has been produced, are shown in Fig. 3.

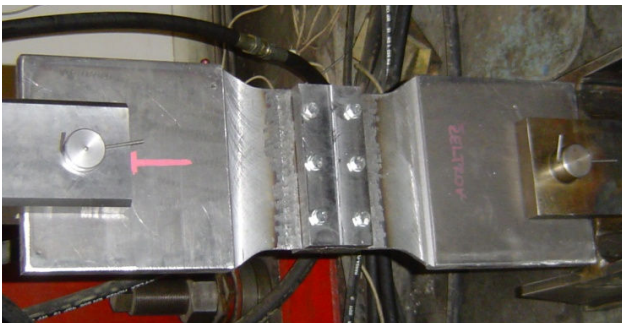


Fig. 3 "Splice-plate" connection: real test specimen (fixed in testing equipment)

III. CYCLIC LOADING TESTS

A. Realization and Progress of Fatigue Tests

The tests of the „splice-plates“ connections subjected to the fatigue effects, which are caused due to cyclic repeated loading, have been realized in the testing room of the Division of Metal and Timber Structures (also see [2]–[4]). In total, 12 test specimens have been verified. For the cyclic loading, the electrohydraulic testing equipment (hydraulic cylinder) with the maximal capacity of 500 kN, respectively 400 kN, has been utilized. The illustrations of cyclic loading tests are demonstrated by Fig. 4 where the testing equipment and structural details of the connection are presented.

B. Results of Fatigue Tests

During the process of fatigue tests the specimens have been subjected to the repeated cyclic loading effects given by the tensile force, which has been being changed in the range given by the value of the minimal force N_{\min} , from which the force was cyclically changed up to the value of the maximal force N_{\max} . Then, the loading force amplitude ΔN is given by the difference $\Delta N = N_{\max} - N_{\min}$. The loading frequency has been determined as the value of $f = 5$ Hz.



Fig. 4 Realization of cyclic loading tests



Fig. 5 Typical failure mechanism: plate fracture in place of bolt holes

The cyclic loading has been realized up to the failure of test specimens, to which the maximal reached number of cycles n corresponds. Loading parameters, i.e. the lower level of the loading force N_{\min} , the upper level of the loading force N_{\max} and the loading force amplitude ΔN are listed in Table I, from which the failure mechanisms occurred in the case of particular test specimens are evident.

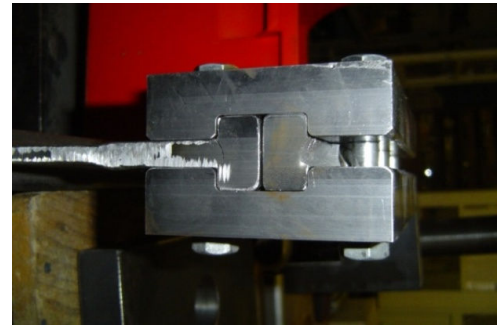
TABLE I
OVERVIEW OF ALL FATIGUE TESTS: LOADING PARAMETERS, REACHED
NUMBER OF CYCLES, FAILURE MECHANISMS

Test	Lower level of loading force N_{\min} [kN]	Upper level of loading force N_{\max} [kN]	Number of cycles n [-]	Failure mechanism
1	10	232	---	test sample
2a	10	491	53 200	plate fracture in place of bolt holes
2b	10	490	69 120	
3	10	489	88 600	
4a	13	236	1 990 000	plate fracture in transition to head
4b	13	236	2 425 000	
5a	13	243	2 835 000	bolt fracture
5b	13	243	5 321 000	plate fracture in place of bolt holes
6a	12	343	468 700	bolt fracture
6b	12	343	1 014 000	
7a	12	344	774 000	plate fracture in place of bolt holes
7b	11	342	609 550	
8	14	346	503 000	cylinder damage
9	11	239	780 000	weld fracture
10	11	239	630 200	
11	12	237	4 822 000	plate fracture in place of bolt holes
12	12	237	6 280 000	

The first test has been intended for the calibration of lower and upper levels of the loading force and for the verification of the testing equipment and loading regime. In this case a small cycle number has been realized, so that the failure has not been monitored and investigated.

In the next tests, the most frequent failure mechanism was the plate fracture in the place of bolt holes (see Fig. 5) occurred in 9 cases. In further cases other particular failure mechanisms occurred: fracture of the plate in transition to the head (see Fig. 6 (a)), bolt fracture, weld fracture (see Fig. 6 (b)).

Unfortunately, in some tests (not included in Table I) the fracture of testing preparations or even the damage of testing equipment occurred. In two cases the fracture of connecting plates in the place of connecting pin (see Fig. 7 (a)) occurred. In one special untypical case the hydraulic cylinder has been damaged (Fig. 7 (b)). These problems have been caused by the constant repetition of high-cyclic loading during fatigue tests of particular test specimens. Therefore it was necessary to repair testing preparations and mainly testing equipment, so the total tests time was much longer than assumed originally.



(a)



(b)

Fig. 6 Illustration of other typical failure mechanisms: a) plate fracture in transition to head; b) weld fracture



(a)



(b)

Fig. 7 Illustration of untypical failure mechanisms – fracture of testing preparations and testing equipment: (a) fracture of connecting plate in place of connecting pin; (b) damage of hydraulic cylinder

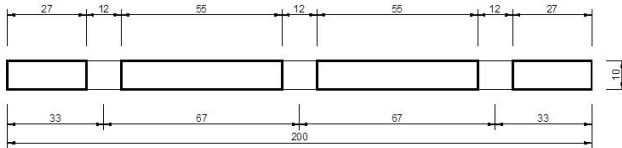
Fig. 8 Plate cross-section area A_{net} in place of bolt holes

Table II lists the overview of parameters needed for the test results evaluation that means the minimal and maximal values of stresses in the failed cross-section σ_{min} and σ_{max} , the corresponding stress amplitude $\Delta\sigma$ and the plate cross-section area A_{net} in the place of the fracture. For the calculation of the stress amplitude $\Delta\sigma$, the plate cross-section area A_{net} in the place of bolt holes, i.e. according to Fig. 8 has been taken.

TABLE II
FATIGUE TESTS RESULTS: AMPLITUDE OF LOADING FORCE AND STRESS

Test	Amplitude of loading force ΔN [kN]	Logarithm of cycle number $\log n$ [-]	Cross-section area A_{net} [mm ²]	Amplitude of stress $\Delta\sigma$ [MPa]
2a	481	4.726	1 640	293.3
2b	480	4.840		292.7
3	479	4.947		292.1
5b	229	6.726		139.6
6b	331	6.006		201.8
7a	332	5.889		202.4
7b	331	5.785		201.8
11	227	6.683		138.4
12	227	6.798		138.4

IV. EVALUATION OF FATIGUE TESTS RESULTS

The evaluation of cyclic loading test results is oriented to the study of the fatigue behavior and the determination of the fatigue strength of the “splice-plate” connections on the base of the test results mentioned in Table II. For these reasons the following methods have been applied: the regression analysis for the study of fatigue behavior, and probability, respectively reliability analysis for the determination of fatigue strength (for evaluation of test results, also see [5]–[8]).

A. Study of Fatigue Behaviour

Basic principles of fatigue behavior of the structural detail subjected to many-times repeated cyclic loading are given by the curve of fatigue strength expressing the dependence of the stress amplitude on the number of loading cycles. To express this relationship, it may be used the logarithmic equation describing Wöhler's curve, which can be transformed into the line, if the logarithmic scale of n -axis is used. Plotting the fatigue test results to the graph, the discrete points can be obtained and then substituted by the line based on the linear regression using the least squares method.

In the first phase of the evaluation, it has therefore been done tentative determination of the stress amplitude, which corresponds to the reference number of 2 million loading cycles. This value can be taken as the first approximation of the permissible stress amplitude, which can be considered as a base for the determination of detail category. This evaluation arising from the mean value determined by the least squares

method does not include more detailed statistical, nor probabilistic evaluation, which should be the base for the determination of the permissible stress amplitude with the required reliability given by the failure probability. The probabilistic evaluation is mentioned below.

The dependence of the stress amplitude on the number of cycles derived using regression analysis is drawn in the graphs in Figs. 9, 10. In Fig. 9 the number of cycles is plotted on the linear scale, while in Fig. 10 it is plotted on the logarithmic scale.

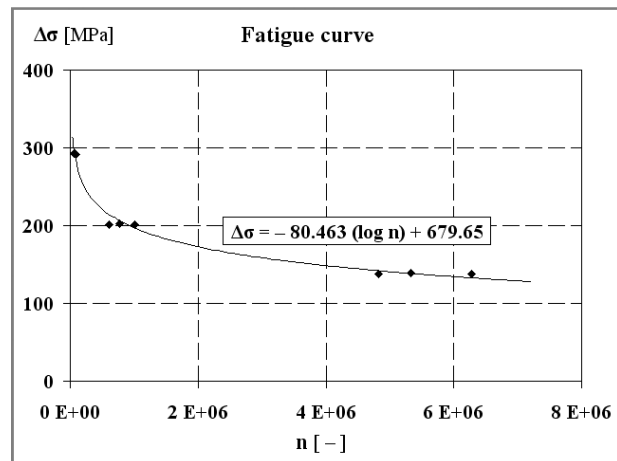


Fig. 9 Dependence of stress amplitude on number of loading cycles (linear scale)

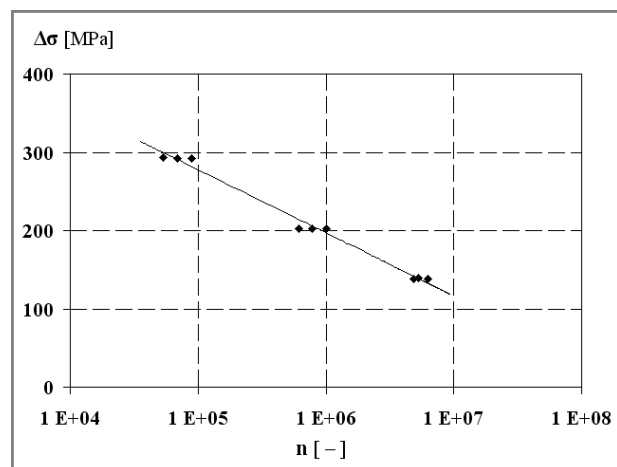


Fig. 10 Dependence of stress amplitude on number of loading cycles (logarithmic scale)

From the equation of the dependence of stress amplitude on the number of loading cycles:

$$\Delta\sigma = 80.463 (\log n) + 679.65 \quad (1)$$

The stress amplitude corresponding to the reference number of 2 million loading cycles ($\log n = 6.301$) has been derived as

$$\Delta\sigma = 172.7 \text{ MPa.}$$

B. Determination of Fatigue Strength

The determination of the fatigue strength has been done according to the methodology elaborated in the informative annex L of the Czech Standard ČSN 73 1401 [11]. The base for the evaluation is logarithmic dependence of the number of cycles realized up to the detail failure on the stress amplitude determined from the loading force, respectively the difference between extremes of loading force of one loading cycle. The essence of the evaluation is the substitution of discrete points obtained plotting the results, by the line based on linear regression, and subsequent statistical evaluation aimed to the determination of the difference of extremes of the loading force of one cycle ΔN_C on the fatigue limit, when constant amplitude, defined for the number of 2 million cycles.

The procedure for the determination of the differences of extremes of the force of one loading cycle contains the gradual determination of the following quantities and parameters:

- parameters α , β of the regression line for the failure probability of 50 %;
- amplitude of the force ΔN_p for $n_C = 2 \cdot 10^6$;
- left-prediction limit n_p (respectively $\log n_p$);
- the difference of loading force extremes of one cycle Δn on the fatigue limit for 2 million cycles.

The regression line, for which the independent variable is the logarithm of the difference of loading force extremes of one cycle ($x_i = \log \Delta N_i$) and the dependent variable is the logarithm of the number of cycles ($y_i = \log n_i$), is expressed by

$$y = \alpha + \beta x, \quad (2)$$

where

$$\beta = S_{xy} / S_{xx}, \quad \alpha = (\Sigma y_i - \beta \Sigma x_i) / p \quad (3)$$

$$S_{xx} = \Sigma (x_i^2) - (\Sigma x_i)^2 / p, \quad S_{yy} = \Sigma (y_i^2) - (\Sigma y_i)^2 / p \quad (4)$$

$$S_{xy} = \Sigma (x_i y_i) - [(\Sigma x_i)(\Sigma y_i)] / p \quad (5)$$

and p is the number of evaluated tests.

For the number of cycles $n_C = 2 \cdot 10^6$, the difference of loading extremes on the regression line is

$$\Delta N_p = (2 \cdot 10^6 / 10^\alpha)^{1/\beta} \quad (6)$$

The left-prediction limit for the difference ΔF_p is

$$\log N_p = \log (2 \cdot 10^6) - t \cdot s_R \cdot \sqrt{F}, \quad (7)$$

where t is γ – critical value of Student distribution $t(v, \gamma)$ for the degree of freedom $v = p - 2$ and the probability of $\gamma = 0.05$; s_R is the standard deviation according to:

$$s_R = [1/(p-2) \cdot (S_{yy} - \beta \cdot S_{xy})]^{1/2} \quad (8)$$

$$f = 1 + 1/p + (\log \Delta n_p - \Sigma x_i/p)^2 / S_{xx} \quad (9)$$

Then, the difference of loading force extremes of one cycle on the fatigue limit for 2 million cycles is

$$\Delta N_C = \Delta N_p (2 \cdot 10^6 / n_p)^{1/\beta} \quad (10)$$

Note: For the values of Student distribution fractiles, the following approximate expression is used:

$$t = 1.645 / \{1 - (1 + 1.645^2)^{-1/2}\} / [4(p-2)] \quad (11)$$

The values of experimental results, which have been obtained from 9 fatigue tests, are summarily listed in Table II. From given values the parameters below have been calculated. Parameters α and β determining the regression line $y = \alpha + \beta x$ have the values of

$$\alpha = 20.58; \quad \beta = -5.859.$$

On the regression line, for the number of cycles $n_C = 2 \cdot 10^6$ the difference of loading force extremes of one cycle is

$$\Delta N_p = 274.1 \text{ kN}.$$

The left-prediction limit for the difference of loading force extremes ΔN_p of one cycle is

$$\log n_p = 6.085.$$

The difference of loading force extremes of one cycle for the determination of the fatigue limit, when constant amplitude, for 2 million loading cycles is then

$$\Delta N_C = 251.8 \text{ kN}.$$

The stress amplitude on the fatigue limit determined for the effective cross-section area $A_{net} = 1\,640 \text{ mm}^2$ is

$$\Delta \sigma_C = 153.5 \text{ MPa}.$$

For the detail investigated it is possible to assign the detail category 140, in accordance with the spectrum of fatigue categories given by the European Standard EN 1993-1-9 [10].

V. CONCLUSION

Some partial results related to the specific structural detail and therefore significantly influenced by this, have already been mentioned in the text above (see Chapter IV.).

From particular test results it is seen that the number of loading cycles reached is in the range from tens of thousands up to several millions (more exactly – see Tables I, II and Figs. 9, 10).

The aim of the evaluation of test results was to investigate the actual behavior of the structural details tested, that means to monitor the types of failure mechanisms occurred at the moment of the fracture of test specimens, i.e. at reaching final number of the loading cycles, and finally, to determine the fatigue category of the structural detail developed.

As expected, the most frequent failure mechanism is the fracture of plates in the place of bolt holes, because the connection has been made so intentionally.

The fatigue category of the investigated structural detail has been determined using the procedures mentioned above and the results are as follows:

The permissible stress amplitude determined from Wöhler's curve for the reference number of loading cycles of 2 million, without consideration of the uncertainties caused by small test number, has been calculated as $\Delta\sigma = 172.7$ MPa. Using the methodology described in the paragraph IV. B, taking into account test numbers and considering the reliability with the failure probability 50 %, the permissible stress amplitude for 2 million loading cycles has been calculated $\Delta\sigma_C = 153.5$ MPa, which is about by 13 % lower than the value $\Delta\sigma$. From there, the fatigue category of the detail can be derived as 140, which correspond with the next lower value given standardly in the appropriate European Standards [9], [10].

In conclusion, the fatigue tests performed have shown that the proposed type of assembly connection has sufficient fatigue resistance, even significantly higher than many other commonly used details.

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