Fatigue Tests of Assembly Joints of Truss Main Girders of Newly Developed Temporary Footbridges

Marcela Karmazínová and Pavel Simon

Abstract**—**The paper is focused on the problems of the actual fatigue resistance of assembly joints of the temporary footbridge for pedestrians and cyclists, which is being newly developed within the framework of the applied research project of the Technological Agency of the Czech Republic. The necessity of the development of a new temporary footbridge has been invoked by the lack of such constructions in a practice, both in the case of flood situations, and also as the site facilities, for pedestrian traffic crossing on the construction sites of bridges or other structures. Within this work the attention is mainly paid to the static and structural design, in particular to the harmonization of aspects of static solution and structural detailing, to achieve the efficient design. In parallel, two types of the footbridge are being developed, both ones with a lower deck, truss main girders and bracings. The first structure, so-called “short footbridge” with a very small self weight, can reach up to 18 m span; the second structure, “long footbridge” with a normal self weight, can reach up to 36 m span. This paper mainly presents the basic information on the actual behaviour of assembly joints of the structure, if subjected to the fatigue loading actions. The content of the paper is focused on the experimental verification of fatigue parameters of the most important structural details and joints. Within the framework of experimental programme, the fatigue tests of exposed details and joints of the truss main girders have been performed. In this paper, the performance of fatigue tests including elaboration and evaluation of their main results are presented.

Keywords**—**Fatigue test, temporary footbridge, truss main girder, assembly joint, lower chord, upper chord, fatigue resistance, detail category, experimental verification, loading test, evaluation.

I. Introduction

THE structures of both footbridges mentioned above are spatial truss systems composed, in principle, of three basic parts: (i) truss main girders resistant mainly to the vertical loading actions, (ii) footbridge deck consisting of cross girders and longitudinal girders, for the introduction of vertical loading actions to the main girders, and (iii) truss bracings resistant mainly to the horizontal loading actions. Basic data about the temporary footbridge development are mentioned in [1] or [4]; more information about the testing methodology is in [2], [3] or [6], for example.

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II. Footbridges Structural Systems

A. Short Footbridge

The short footbridge (Fig. 1) is composed as the structure with a lower deck and two truss main girders with the axial distance of 2 360 mm and theoretical height of 1 390 mm. The length of one segment of the main girder is 1 000 mm. Main girders are composed of parallel straight chords, diagonals and verticals. The footbridge spatial rigidity is ensured by longitudinal horizontal truss bracing.

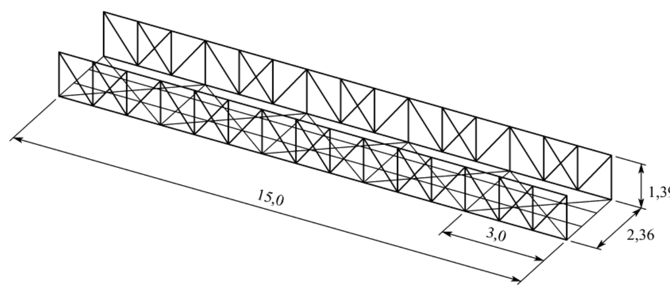

Fig. 1 Composition and geometric parameters of short footbridge main load-carrying structure

The chords of truss main girders are rectangular tubes; the dimensions of the upper chord cross-section are $100 \times 60 \times 4$, dimensions of the lower chord section are $80 \times 80 \times 4$. Dimensions of diagonals and verticals (excluding transverse frames – see below) are $40 \times 40 \times 3.2$.

The load-carrying structure of the footbridge deck is composed of cross and longitudinal girders. Cross girders with the axial distance of 3.0 m are placed between lower chords of the main girders. Longitudinal girders with the axial distance of 0.72 m and 0.82 m, respectively, are placed between cross girders. The sections of cross girders are profiles of IPE 140; longitudinal girders are rectangular tubes with the dimensions of $80 \times 40 \times 4$.

The stability of the compression upper chords of main girders is ensured by the system of the transverse frames in the distance of 3.0 m. Transverse frames are composed of cross girders and verticals (profiles of IPE 140), and they are structured with a sufficient flexural stiffness, to can support the compression upper chords of main girders in horizontal direction.

The footbridge structure has one longitudinal bracing only, in horizontal level of the footbridge deck. The deck longitudinal bracing is structured as the truss plane girder of rhombic system, mainly resistant to the transverse horizontal actions, i.e. transverse wind load. The chords of the longitudinal bracing are represented by the lower chords of main girders; the verticals are cross girders; the diagonals have rectangular cross-section with the dimensions of 40 × 5.

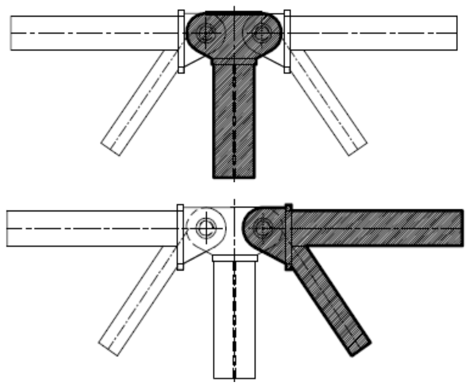

Fig. 2 Structural detailing of assembly joints of truss main girder upper chord of short footbridge

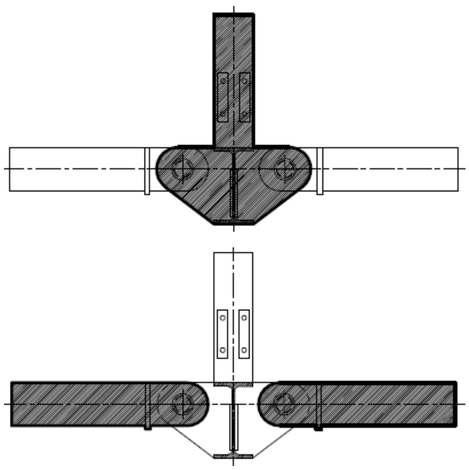

Fig. 3 Structural detailing of assembly joints of truss main girder lower chord of short footbridge

The structure is divided into assembly parts, which are being connected by assembly joints. They are located on upper and lower chords of main girders in the places of transverse frames in the distances of 3.0 m, in accordance with main girder assembly segments. Structural detailing of connections of upper and lower chords of main girders is evident from Figs. 2 and 3.

B. Long Footbridge

The long footbridge (see Fig. 4) is composed as the structure with a lower deck and two truss main girders with the axial distance of 2 360 mm and theoretical height of 2 670 mm. The length of one segment of the main girder is 3 000 mm. The geometrical system of the main girder is composed of the parallel straight chords, diagonal and vertical members; the diagonals are crossed. The spatial rigidity of the footbridge is ensured by longitudinal horizontal truss bracings.

The chords of truss main girders are rectangular tubes; the dimensions of upper chord cross-section are 100 × 100 × 4, the dimensions of the lower chord are 140 × 80 × 4. The vertical members of truss main girders are also rectangular tubes with cross-section dimensions of 140 × 140 × 5; the diagonal members have a circular cross-section with a diameter of 30 mm.

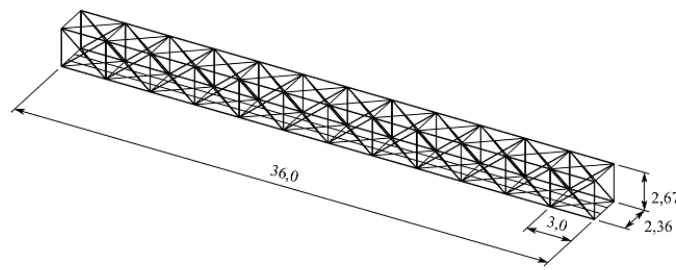

Fig. 4 Composition and geometric parameters of long footbridge main load-carrying structure

The load-carrying structure of the footbridge deck is composed of cross and longitudinal girders. Cross girders with the axial distance of 3.0 m are placed between lower chords of the main girders. Longitudinal girders with the axial distance of 0.72 m and 0.82 m, respectively, are placed between cross girders. Both cross girders, and longitudinal girders are rectangular tubes with cross-sections of 80 × 40 × 4.

Fig. 5 Structural detailing of assembly joint of truss main girder upper chord of long footbridge

Fig. 6 Structural detailing of assembly joint of truss main girder lower chord of long footbridge

The footbridge structure has lower and upper bracings. Two longitudinal bracings are used: the lower bracing at horizontal level of the footbridge deck and the upper one at the level of the main girder upper chords. Both longitudinal bracings are structured as the truss plane girders of rhombic system, mainly resistant to the transverse horizontal actions, i.e. transverse wind load. Chords of the lower longitudinal bracing are represented by the lower chords of main girders; the verticals are cross girders; the diagonals are circular tubes with the cross-section of TR 33.7 × 2.6. The chords of the upper longitudinal bracing are represented by the upper chords of the main girders; the verticals are rectangular tubes with cross-section 140 × 140 × 5; the diagonals are circular cross-sections with the diameter of 16 mm.

III. Philosophy and Methodology of Fatigue Tests

A. Aims of Fatigue Tests

The aim of fatigue tests of structural details of steel footbridge structure were to verify the behaviour of the details subjected to the loading actions corresponding to the actual loads caused by the operating traffic, and based on the results to derive the structural lifetime and durability, and respectively, to predict the behaviour of the footbridge structure in the real traffic conditions with regard to influence of repeated cyclic load, and to define possible fatigue damage.

B. Basic Assumptions and Principles

Generally it is known, from the viewpoint of cyclic loading and possible fatigue damage the most adverse stress is alternating stress, when the sign of normal stress in cross-section is alternately changed, that means the tension and compression in investigated cross-section part alternate. However, in the case of the footbridge structure developed this status cannot practically occur, because of the relevant loading situations and their combinations. For this reason, in our case the most adverse stress is tensile stress, when the changes of stresses in tension only occur. Due to this fact the fatigue tests are concentrated to the verification of the tensile effects in lower chords, among others for the reason of practical realization of fatigue loading tests.

With regard to the requirement for the assembly able construction, the joints of truss main girders are structured using welded production connections and pin assembly connections, which allow their repeatable assembly and disassembly. Due to the fact, that there are not typical details, whose mutual interaction and influence cannot be clearly determined or estimate in advance, it was decided to test the connections as a whole, not separately individual details, with a view to determine the lifetime and durability of the entire joint as a newly developed recommended type of structural detail, which is usable for the assembled connection of assemble able structures mentioned, not only isolated details.

C. Considered Conception

For the verification and evaluation of the fatigue effects on the lifetime of proposed joints, two basic approaches (partially see above) following preliminary expected fatigue resistances determined according to European Standards, have been considered. Based on the assumed operating loads, their intensities, assumed lifetime and classification of the joint to the corresponding detail category, the fatigue evaluation of exposed details have been performed using European Standard rules. This evaluation consisted the calculation of stress amplitudes for the assumed operating load, which in accordance to the assumed lifetime, have been taken as the bases for the derivation of specific parameters of loading effects applied during loading tests, i.e. in particular the amplitude of the loading force given by the stress amplitude, in addition with regard to the fact, that for the evaluation of the results of fatigue tests is efficient to load on more various force levels or for more various amplitudes, to be obtained the more diverse spectrum of the results, which can be subsequently statistically elaborate.

D. Regime of Loading

The initial phase of the introduction of tensile force has been realized, that at the beginning the force has been linearly increased up to the provided default chosen middle value F_m, from which the force has been cycled in the range from F_{min} to F_{max} according to the provided amplitude ΔF of loading forces. Thus, in the control unit of the hydraulic servo cylinder, at the beginning of the loading procedure two values have been set – default middle force F_m and given amplitude F_a, which together represented amplitude $\Delta F = F_m + F_a = F_{max} - F_{min}$. The criteria for automatic switching-off the cycling, given by the limitation of the entire deformation, i.e. mutual displacement of test specimen parts, has been determined by the value of 50 mm.

IV. Practical Realization of Fatigue Tests

A. Short Footbridge

In total 6 assembly joints of lower and upper chords have been produced for fatigue tests. The shape and dimensions of test specimens have been derived from the actual composition of real joints (see Figs. 2 and 3). The first 3 specimens of the lower chord have been produced including the part of transverse frame (see Fig. 7). The next 3 specimens of the upper chord have been produced without transverse frame (see Fig. 8), because this part does not influence the fatigue behaviour of the connection.

Loading tests have been performed for 6 specimens made (see figures above). For the first test the force amplitude has been chosen by the value of ΔF = 100 kN (force in the range from 50 kN to 150 kN), for the next tests the amplitude was ΔF = 70 kN (force in the range from 50 kN to 120 kN).

Loading tests have been performed on specimens consisting of the middle part represented by the sheet (and transverse frame, respectively) and of two connecting end parts of the chord members (see Figs. 9 and 10). In the most cases (except one only) the same failure of the end chord parts near the welds occurred (see below). If the failure on one side of the joint occurred after the certain number of cycles, this part has been replaced by a new one, and the test continued. If the further failure occurred, this process has been repeated, while the resulting number of the cycles N (see Table 1 below) has been obtained as the sum of the number of cycles realized in each of the individual stages of the loading process.

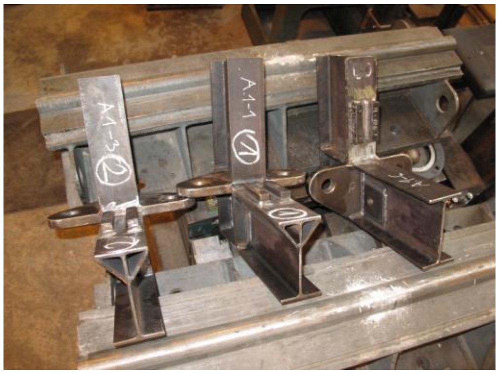

Fig. 7 Illustration of produced assembly joints of short footbridge main girder lower chord: specimens including transverse frame

Fig. 8 Illustration of produced assembly joints of short footbridge main girder upper chord: specimen not-including transverse frame

Fig. 9 Illustration of tests of short footbridge main girder lower chord: specimen including transverse frame

Fig. 10 Illustration of tests of short footbridge main girder lower chord: specimen not-including transverse frame

B. Long Footbridge

In total 3 joints of lower chord have been verified using fatigue tests. The shape and dimensions of test specimens have been derived from the actual configuration of real joints (see Figs. 5 and 6). Illustration of the test specimen produced is in Fig. 11.

Fig. 11 Illustration of produced assembly joints of long footbridge main girder lower chord

Loading tests of lower chord joints have been performed for 3 specimens made (see above). The force amplitude has been chosen by the values of ΔF_1 = 119 kN (tensile force in the range from 25 kN to 144 kN), ΔF_2 = 97 kN (in the range from 25 kN to 122 kN) and ΔF_3 = 75 kN (in the range from 25 kN to 100 kN).

Loading tests have been performed on specimens consisting of the middle part represented by the sheet and two connecting end parts of the chord members (see Fig. 12). During cyclic tests individual members have been continuously tested and after the failure or reaching more than 2 million cycles have been replaced by the new part. Thus several parts of the test specimens could be tested within one test with the chosen force amplitude ΔF. Then the resulting number of the cycles N (see Table 2 and Table 3 below) has been obtained as the sum (cumulating) of the numbers of cycles realized in each of the individual stages of the loading process.

For the transparency, the parts of tested members of truss main girder lower chord have been marked as follows: VD – end of the lower chord of truss main girder with the connected part with the hole for the pin; MS – middle part with the holes for pins, including the connected vertical part.

Fig. 12 Illustration of tests of long footbridge main girder lower chord

V. Results of Fatigue Tests

A. Short Footbridge

In one case the test specimen did not fail even after reaching 2 million cycles and the test has been finished, in all other cases, the failure of the end parts of chords near the welds connecting the end plate (with sheets for the pin) to the chord profile occurred. Examples of the typical failures for individual test specimens are illustrated in Figs. 13 and 14.

Fig. 13 Illustration of typical fatigue failure – cracks near welds on end parts of lower chords: specimen including transverse frame

Fig. 14 Illustration of typical fatigue failure – cracks near welds on end parts of lower chords: specimen not-including transverse frame

Table 1 Results of fatigue tests – short footbridge main girder chords: failure of welds

Test specimen		Force amplitude ΔF [kN]	Number of cycles N
TD 1	TD 1/1	100	39 500
TD 2	TD 2/1	70	1 336 000
	TD 2/2		1 336 000
TD 3	TD 3/1		842 000
	TD 3/2		1 268 298
TD 4	TD 4/1		1 219 500
	TD 4/2		2 451 500
TD 5	TD 5/1		3 165 000
TD 6	TD 6/1		1 069 000
	TD 6/2		644 000

The direct results are the numbers of repeated loading cycles reached at the time of fatigue failure. The overview of all tested specimens, including basic loading parameters applied during fatigue tests, and mainly the resulting number of cycles is listed in Table 1.

B. Long Footbridge

The fatigue failure of the joints occurred by two basic modes: failure (fracture) of the pin (see Fig. 15) or failure (cracks) in the base material around the holes for pins, either on the ends of connected members (see Fig. 16), or on the sheet of the middle part of joint (see Fig. 17). No failure of the welds occurred, even nor after reaching maximal number of cycles realized for the defined force amplitudes.

Because of two various basic failure modes and their different characters, it was not possible to evaluate the fatigue tests results together for entire joint, although from the test results evaluation for pins and for sheets with holes it is evident, that one of these failure mechanisms only, which will occur earlier, will be finally determining for the derivation of the lifetime and durability. Thus, the evaluation of the fatigue test results for the joints of truss main girder lower chord included the evaluation of the detail category arising from both basic failure mechanisms.

Fig. 15 Illustration of typical fatigue failure – failed pins

The direct results are the numbers of repeated loading cycles reached at the fatigue failure. The overview of all tested specimens, including basic loading parameters applied during fatigue tests, and mainly the resulting number of cycles is listed in Table 2 and Table 3.

Fig. 16 Illustration of typical fatigue failure – cracks around holes for pins: chord end part

Table 2 Results of fatigue tests – long footbridge main girder lower chord: failure of pins

Test specimen	Force amplitude ΔF [kN]	Number of cycles N
VD1	119	382 000
MS1		296 000
VD2		1 431 000
MS2		1 727 000
VD3	97	1 572 000
MS3		2 782 000
VD4	75	3 404 000

Fig. 17 Illustration of typical fatigue failure – cracks around holes for pins: joint middle part

Table 3 Results of fatigue tests – long footbridge main girder lower chord: cracks around holes for pins: VD – end part of chord; MS – middle part of joint

Test specimen	Force amplitude ΔF [kN]	Number of cycles N
VD1	119	382 000
MS1		296 000
VD2		1 431 000
MS2		1 727 000
VD3	97	1 572 000
MS3		2 782 000
VD4	75	3 404 000

VI. Fatigue Resistance

A. Basic Principles

Because the most failure type was the failure of pins and until subsequently the failure of other parts occurred, that failure of pins has been taken as default for the evaluation of cyclic fatigue tests. Other various failure modes did not have to be taken into account here. The aim of the evaluation of the fatigue resistance was to determine the fatigue detail category, which is influenced by behaviour of joint as a whole, as a result of its specific configuration given by the individual partial notches. Thus, the standard fatigue detail category of the corresponding pins cannot be clearly applied.

B. Determination of Fatigue Resistance

The evaluation of the results of fatigue tests has been elaborated using the methodology of the standard ČSN 73 1401 Design of Steel Structures [9]. The base for the evaluation is the logarithmic dependence between the number of cycles (up to the failure) and the stress amplitude determined from the loading force amplitude ΔF (see above). The principle of evaluation is the substitution of the discrete test points by the line based on the linear regression and subsequent statistic and probabilistic evaluation aimed to determine the detail category, i.e. the stress amplitude for the given number of cycles N_C, standard for $N_C = 2 \cdot 10^6$.

The procedure of the detail category evaluation includes the determination of following quantities and parameters: parameters α, β of the regression line for the failure probability of 50 %; the stress amplitude $\Delta\sigma_P$ for $N_C = 2 \cdot 10^6$; the left-side prediction limit N_P; stress amplitude $\Delta\sigma_C$. The regression line is expressed by the equation of $y = \alpha + \beta\, x$ (below, n is the number of tests evaluated)
where

$$\beta = S_{xy} / S_{xx}, \;\; \alpha = (\Sigma y_i - \beta\, \Sigma x_i) / n, \tag{1}$$

$$S_{xx} = \Sigma(x_i^2) - (\Sigma x_i^2) / n, \tag{2}$$

$$S_{yy} = \Sigma(y_i^2) - (\Sigma y_i^2) / n, \tag{3}$$

$$S_{xy} = \Sigma(x_i\, y_i) - [(\Sigma x_i)\, (\Sigma y_i)] / n, \tag{4}$$

For the number of cycles of $N_C = 2 \cdot 10^6$ stress amplitude on the regression line is

$$\Delta\sigma_P = (2 \cdot 10^6 / 10^{\alpha})^{1/\beta} \,. \tag{5}$$

The left-side prediction limit for stress amplitude of $\Delta\sigma_P$ is

$$\log N_P = \log (2 \cdot 10^6) - t\, s_R \sqrt{f}, \tag{6}$$

where t is γ-critical value of Student distribution $t\,(\nu, \gamma)$ for $\nu = n - 2$ and probability of $\gamma = 0.05$; parameters s_R (standard deviation) and f are given by the formulas of

$$s_R = [\, 1/(n-2)\, (S_{yy} - \beta\, S_{xy})\,]^{1/2} \,, \tag{7}$$

$$f = 1 + 1/n + (\log \Delta\sigma_P - \Sigma x_i / n)^2 / S_{xx}. \tag{8}$$

Then stress amplitude for the determination of the detail category is

$$\Delta\sigma_C = \Delta\sigma_P\, (2 \cdot 10^6 / N_P)^{1/\beta}. \tag{9}$$

That basic form of the procedure mentioned above with normal stress amplitude $\Delta\sigma$ has been utilized for the detail category evaluation in the case of the failure of the welds (see Figs. 13 and 14) or sheets with holes (see Figs. 16 and 17), which are subjected by normal stress changes. Alternatively, this procedure can be analogically modified for shear stress amplitude, using $\Delta\tau$ instead of $\Delta\sigma$. That modification of the procedure has been utilized for the detail category evaluation in the case of the failure of pins (see Fig. 15) subjected to shear stress changes.

VII. Evaluation of Test Results

A. Short Footbridge

Below the determination of fatigue detail category is shown using the example of the failure of welds (for fatigue parameters see Table 1).

The total number of the tests performed was 13, but by detail analysis it was found, that 3 results of total test number cannot be evaluated because of the statistical reasons, therefore 10 results only have been taken for the evaluation for the fatigue resistance given by the fatigue detail category. The relationships between the number of cycles and stress amplitude are shown in Fig. 18. Applying the procedure above the resulting category of the fatigue detail has been derived as $\Delta\sigma_C = 43$ MPa.

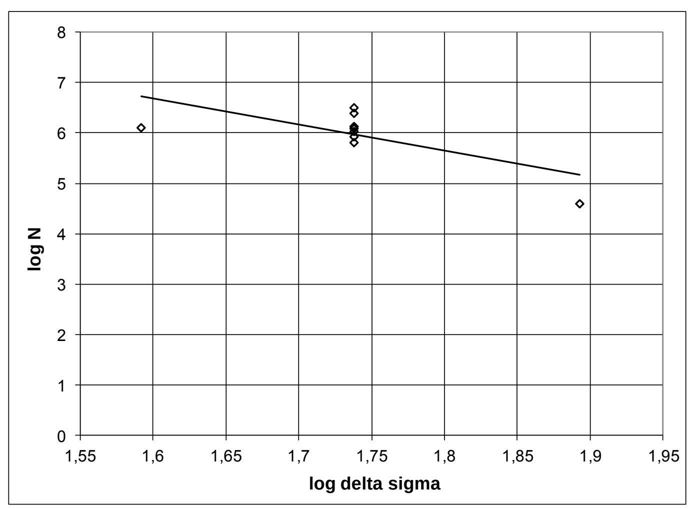

Fig. 18 Relationships between normal stress amplitude and number of cycles: short footbridge main girder chords – failure of welds

For the verification, whether the evaluation mentioned above is real from the viewpoint of usual situations and experiences of static designers, the simplified derivation of the detail category has been performed. From the graph in Fig. 19 the value of stress amplitude has been deducted. The logarithm of the number of cycles $2 \cdot 10^6$ is $\log (2 \cdot 10^6) = 6$; the logarithm of stress amplitude is $\log \Delta\sigma = 1.73$; then the corresponding value of the stress amplitude is $\Delta\sigma = 53.7$ MPa ≈ 54 MPa. This value approximately corresponds to the fatigue detail category prescribed in the standard [8] for weld type given. It can be deducted, that resulting categories obtained by test results evaluation regarding their number and limit failure probability are real, while they include the required reliability. It is necessary to accent, that the value taken from graphs in Fig. 15 represents the mean value, in addition obtained from a small number of the tests that means it should be reduced with regard to the variability and uncertainties of the actual behaviour.

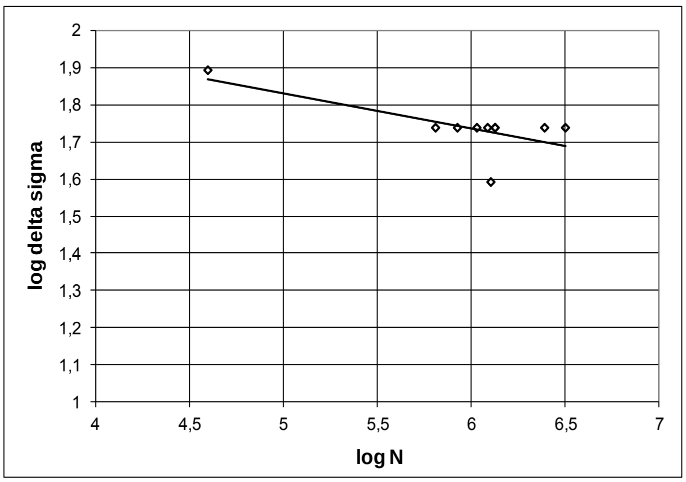

Fig. 19 Relationships between number of cycles and normal stress amplitude: short footbridge main girder chords – failure of welds

B. Long Footbridge

Below the determination of fatigue detail category is shown using the example of the failure of pins (for fatigue parameters see Table 2).

The total number of performed tests was 7 only. The relationship between the number of cycles and stress amplitude is shown in Fig. 16. Applying the procedure above the resulting category of the fatigue detail has been derived as $\Delta\tau_C = 30.1$ MPa.

To verify, whether the evaluation mentioned above is real from the viewpoint of usual situations and experiences of static designers, the simplified derivation of the detail category has been performed. From the graph in Fig. 16 the value of stress amplitude has been deducted. The logarithm of the number of cycles $2 \cdot 10^6$ is $\log (2 \cdot 10^6) = 6$; corresponding value of stress amplitude is $\Delta\tau = 36.4$ MPa. This value is a little higher than above, but from here it can be deducted, that resulting categories obtained by test results evaluation regarding their number and limit failure probability are real, while they include the required reliability. It is necessary to accent, that the value taken from graphs in Fig. 16 represents the mean value, in addition obtained from a small number of the tests that means it should be reduced with regard to the variability and uncertainties of the actual behaviour.

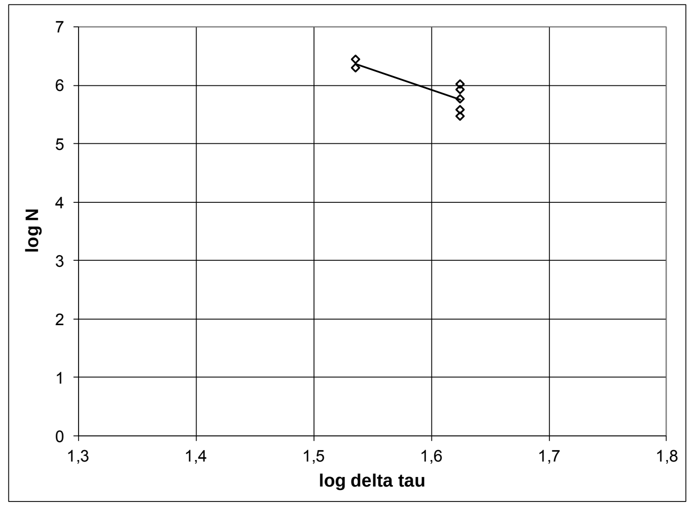

Fig. 16 Relationships between shear stress amplitude and number of cycles: long footbridge main girder chord – failure of pins

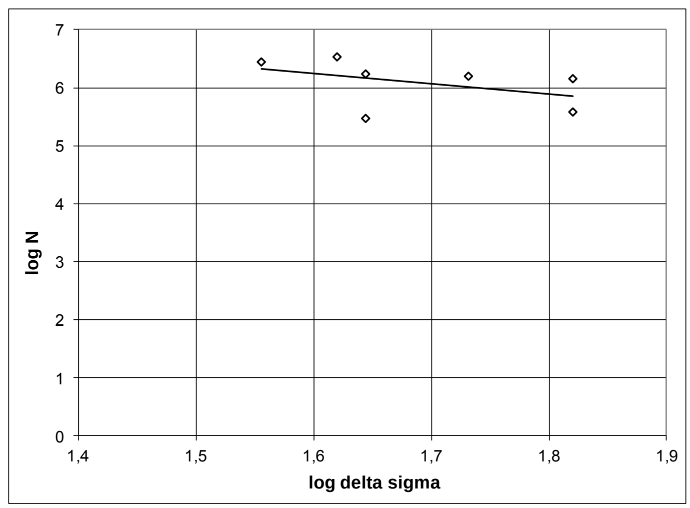

Fig. 17 Relationships between normal stress amplitude and number of cycles: long footbridge main girder chord – failure by cracks in sheets with holes for pins

Below the determination of fatigue detail category is shown using the example of the failure by cracks in sheets with holes (for fatigue parameters see Table 3).

The total number of the tests performed was 7 only. The relationship between the number of cycles and stress amplitude is shown in Fig. 17. Applying the procedure above the resulting category of the fatigue detail has been derived as $\Delta\sigma_C = 11.7$ MPa.

VIII. Conclusions

From the viewpoint of the specific values obtained evaluating a small number of the specimens and from the viewpoint of the prediction of the behaviour of tested details, it is necessary to take into account, that the actual behaviour of the joints included to the structural system can be negatively, but also positively influenced by the entire composition of load-carrying structure, i.e. by the effect of individual connecting members and configuration of their details. Because the resulting detail categories evaluated based on the tests are relatively low (lower than categories corresponding to the investigated detail and given by the standard), the process of the evaluation of the suitability of used detail has been selected, that actual behaviour of the joint should be safe. This requirement invoked subsequent structural modifications, i.e. the strengthening of cross-section of chord members and connecting welds, to reach the reliable reserve.

From the viewpoint of the specific values obtained evaluating a small number of the specimens and from the viewpoint of the prediction of the behaviour of tested details, it is necessary to take into account, that the actual behaviour of the joints included to the structural system can be negatively, but also positively influenced by the entire composition of load-carrying structure, i.e. by the effect of individual connecting members and configuration of their details. Because the resulting detail categories evaluated based on the tests are low, such process of the evaluation of the suitability of used detail has been selected, that actual behaviour of the joint should be safe.

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