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Fatigue resistance and durability of new mechanical connections of currently developed temporary steel footbridges and railway bridges

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Abstract

On the workplace of paper authors', the experimental studies of the fatigue behaviour and fatigue resistance of several new types of steel mechanical connections have been performed recently. The problems of mechanical connections mentioned above have been solved in the past within the projects of the development of new types of advanced temporary steel bridges and footbridges, with the support of the programme of applied research, development and innovations of the Technology Agency of the Czech Republic. These newly developed connections represent the assembly joints based on the bolts and pins together with plates. Within this investigation, fatigue tests of connections have been performed. The experimental studies have been oriented to the verification of the behaviour of those connections and especially, the fatigue strength, and subsequently the fatigue resistance and durability of the structural detail according to the configuration and structural design.

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Keywords: Fatigue; resistance; durability; steel; temporary footbridge; railway bridge; mechanical connection; cyclic loading; failure mode; detail category; experimental verification; loading test; evaluation.

1. Introduction

In the first part of our work, the experimental verification of the fatigue resistance of assembly connections of newly developed temporary steel footbridges with truss main girders, have been carried out. All these joints have been designed using pins and plates. Within their investigation, the fatigue tests of assembly joints namely of lower chords, which are subjected to the tensile force, have been performed [3, 4, 5].

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In the second part of the work, the experimental verification of the fatigue resistance of special types of assembly joints conceptually intended for perspective temporary steel railway bridges, has been performed. All these connections have been designed using bolts and plates. Within the investigation, the static tests and then also the fatigue tests of two types of currently developed joints subjected to the tensile force have been realized [1, 2].

After realization of the fatigue tests, the elaboration and evaluation of test results have been carried out. In the first step of the elaboration, the test results obtained have been evaluated from the viewpoint of the load amplitude in relation to the number of loading cycles, to obtain the simple fatigue strength only [1, 3, 4, 7, 8]. In the second step of the elaboration, the test results have been statistically and probabilistically evaluated, to obtain the reliable fatigue strength, also with regards to the test number and the required level of the reliability [1, 3, 4, 6, 9].

2. Connections of temporary steel footbridges

2.1. Structural systems of footbridges and detailing of connections

The so-called short footbridge can reach up to 18 m span, has a lower bridge deck and truss main girders with the height of 1 390 mm in the axial distance of 2360 mm. Main girders consist of individual assembly structural components with the length of 3000 mm, which are further divided into partial segments of the length of 1000mm. The footbridge spatial rigidity is ensured by longitudinal horizontal truss bracing. The geometrical composition of the short footbridge and typical arrangement of its connections of upper and lower chords are illustrated in Fig. 1.

The so-called long footbridge can reach up to 36m span, also has a lower bridge deck and truss main girders with the height of 2670 mm in the axial distance of 2360mm. Similarly as in the case of short footbridge, main girders consist of assembly structural components with the length of 3000mm, which further are not divided. The footbridge spatial rigidity is ensured by longitudinal horizontal truss bracing. The geometrical composition of the long footbridge and typical arrangement of its assembly joints of upper and lower chords are illustrated in Fig. 2.

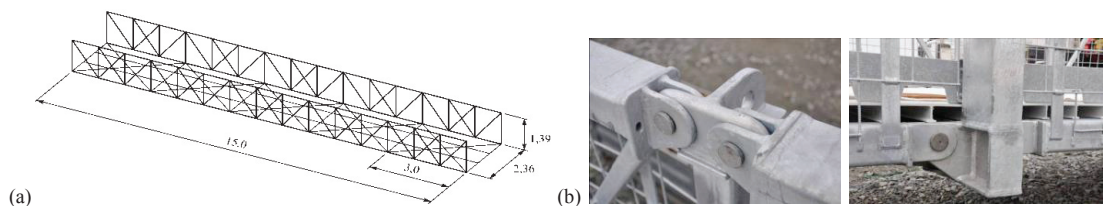


Fig. 1. Short footbridge: (a) geometrical composition; (b) typical configuration of assembly connections (upper and lower chords).

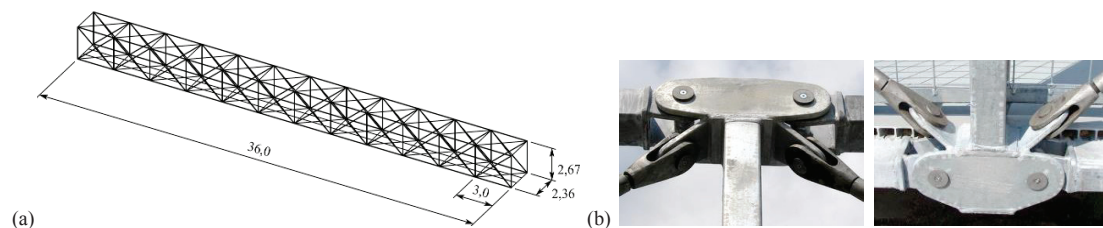


Fig. 2. Long footbridge: (a) geometrical composition; (b) typical configuration of assembly connections (upper and lower chords).

2.2. Methodology of fatigue tests

The aim of fatigue tests was to verify the behaviour of the connections subjected to loading actions corresponding to the actual loads caused by the operating traffic, and to derive the fatigue resistance. It is generally known the most adverse stress is alternating stress, when tension and compression alternate. However, in the case of these footbridge structures, this status practically cannot occur. Here, the changes of tensile stress, the most adverse from the viewpoint of fatigue, just occur. Due to this fact, the fatigue tests were concentrated to the verification of tensile

effects in lower chords. Main girder joints are structured using the combination of welded connections and pin connections, which allow the repeatable assembly and disassembly. They are not typical details, whose mutual interaction and influence cannot be clearly determined or estimated in advance, so that it was decided to test the joints as a whole, with a view to determine the lifetime and durability of the entire joints as newly developed recommended types of structural details usable for assembly joints. For more to the testing methodology, see [5].

The initial phase of tensile force introduction 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 . Thus, at the beginning of the loading procedure two values have been set – default middle force F_m and given amplitude F_a , which represented amplitude of loading forces $\Delta F = F_m + F_a = F_{max} - F_{min}$. The criterion of the automatic shut-off of load applying has been given by the limit of total deflection, i.e. the relative position of the specimen parts, and it has been set as the value of 50mm. From the viewpoint of measuring centre setup (in terms of the realization of tensile force by hydraulic equipment), force-controlled loading has been applied. The frequency of loading cycle f has been chosen as 5Hz (with sinusoidal amplitude). The sampling rate of induction position sensors has been set to 100Hz per channel

2.3. Fatigue tests of short footbridge connections

In total 6 joints of lower chord have been manufactured for the fatigue tests; three specimens were the same as actual joints, including the part of transverse frame, and other three specimens have been manufactured simplified, without transverse frame (both in Fig. 3a), because this part does not influence the fatigue behaviour of the joint. For the first test the force amplitude has been chosen as $\Delta F = 100\text{kN}$ (force in the range from 50 to 150kN), for the next tests the amplitude was $\Delta F = 70\text{kN}$ (force in the range from 50 to 120kN).

Loading tests have been performed on specimens consisting of the middle part represented by the sheet and of two connecting end parts of the chord members. In most cases the failure of end chord parts near the welds occurred. If the failure on one side of the joint occurred, this part has been replaced by a new one, and the test continued. If the further failure occurred, this process has been repeated; resulting number of cycles N is the sum of number of cycles in each individual stage. In one case the test specimen did not fail nor after reaching 2 million cycles and the test has been finished; in all other cases, the failure of end parts of chords near the welds connecting the end plate to chord profile occurred. Typical failures of test specimens are shown in Fig. 3b. The overview of fatigue tests results, including basic loading parameters applied during fatigue tests is in Table 1 – for more see [3].

Because the most failure type was the failure near the welds initiating the fatigue cracks and until subsequently the failure of other parts occurred, so the failure in the welds has been taken as default for tests evaluation. The evaluation aim was to determine the fatigue detail category influenced by the behaviour of the connection as a whole. From the graphs in Fig. 4, the mean value of stress amplitude has been derived as $\Delta\sigma = 53.7\text{MPa}$ for the number of cycles $2 \cdot 10^6$. This value approximately corresponds to detail category prescribed in [8] for given weld.

Table 1. Short footbridge connections – fatigue tests results: typical failure mode – failure of end parts near welds

Test specimens		Loading force [kN]		Force amplitude ΔF [kN]	Resulting number of cycles N
		F_{min}	F_{max}		
TD 1	TD 1/1	50	150	100	39 500
TD 2	TD 2/1	50	120	70	1 336 000
	TD 2/2	50	120	70	1 336 000
TD 3	TD 3/1	50	120	70	842 000
	TD 3/2	50	120	70	1 268 298
TD 4	TD 4/1	50	120	70	1 219 500
	TD 4/2	50	120	70	2 451 500
TD 5	TD 5/1	50	120	70	3 165 000
TD 6	TD 6/1	50	120	70	1 069 000
	TD 6/2	50	120	70	644 000

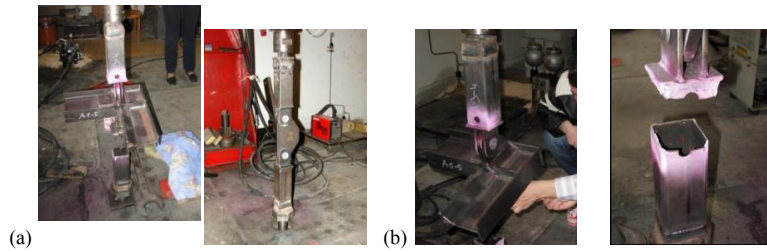


Fig. 3. Connections of short footbridge: (a) two types of tested specimens – with and without transverse frame (simplified); (b) typical failure mode – failure of end parts near welds.

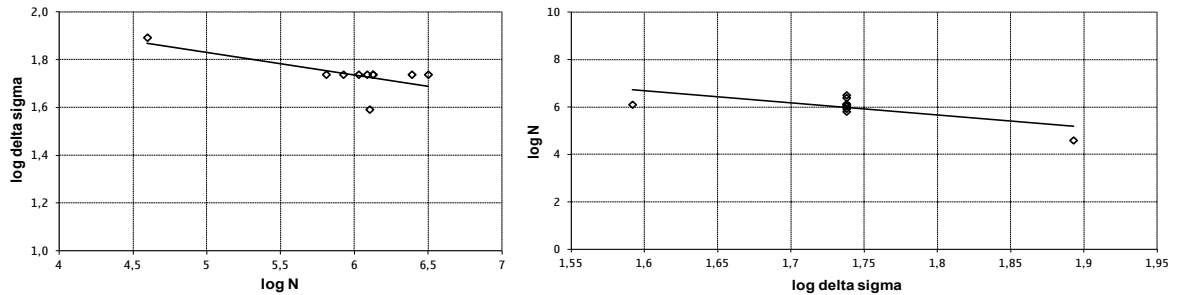


Fig. 4. Connections of short footbridge – relationships between number of cycles and stress amplitude: failure of end parts near welds.

2.4. Fatigue tests of long footbridge connections

In total 3 connections 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 connections. Illustration of the test specimen manufactured is in Fig. 5a (left). Loading tests of lower chord connections have been performed for 3 specimens made. The force amplitude has been chosen by the values of $\Delta F_1 = 119\text{kN}$ (tensile force in the range from 2 kN to 144kN), $\Delta F_2 = 97\text{kN}$ (in the range from 25kN to 122kN) and $\Delta F_3 = 75\text{kN}$ (in the range from 25kN to 100kN).

Loading tests have been performed on specimens consisting of the middle part represented by the sheet and of two connecting end parts of the chord members (Fig. 5a right). 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 (Table 2) has been obtained as the sum (accumulation) 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 and numbered, as follows: MS – middle part with the holes for pins; VD – end of the lower chord of truss main girder with the connected part with the hole for the pin.

The fatigue failure of the connections occurred by two basic modes: failure (fracture) of the pins (Fig. 5b left) or failure (cracks) of the base material around the holes for pins in the sheet or in the ends of connected members (Fig. 5b right). No failure of the welds occurred, even 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 impossible to evaluate the fatigue tests results together for entire connection, 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. 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 – for more see [4].

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.

The total number of the tests performed was 7 only. The relationship between the number of cycles and stress amplitude is shown in Fig. 6. From the graph the value of stress amplitude has been deduced. 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.

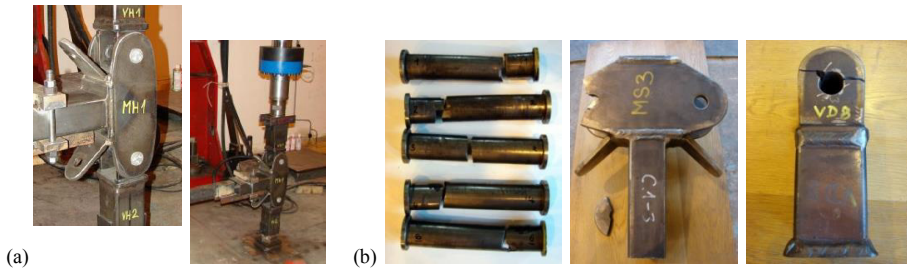


Fig. 5. Connections of long footbridge: (a) test specimen and test arrangement – specimen installed in testing equipment, testing process; (b) typical failure modes – pin failure, failures of middle part (MS) and end part (VD) around holes for pins.

Table 2. Long footbridge connections – fatigue tests results: typical failure modes

Failure of pins			Failure of base material around holes for pins in sheet of middle part or in end parts		
Test specimens	Force amplitude ΔF [kN]	Number of cycles N	Test specimens	Force amplitude ΔF [kN]	Number of cycles N
P 1	119	845 000	MS 1	119	296 000
P 2	119	1 049 000	VD 1	119	382 000
P 3	119	586 000	MS 2	119	1 727 000
P 4	119	382 000	VD 2	119	1 431 000
P 5	119	296 000	MS 3	97	2 782 000
P 6	97	1 993 000	VD 3	97	1 572 000
P 7	97	2 782 000	VD 4	75	3 404 000

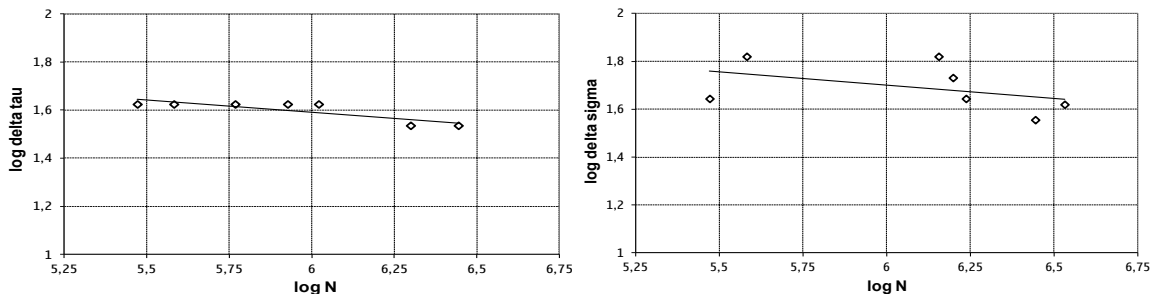


Fig. 6. Connections of long footbridge – relationships between number of cycles and stress amplitude: failure of pins (left), failure of base material around holes for pins in sheet of middle part or in end parts (right).

3. Connections of temporary steel railway bridges

3.1. Structural detailing of developed connections

The 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 tensile force is transferred from one member to the splice plates by mutually locking 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 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. The principle scheme of investigated connection is drawn in Fig. 7, as well as the illustrations of manufactured test specimen installed in the testing equipment.

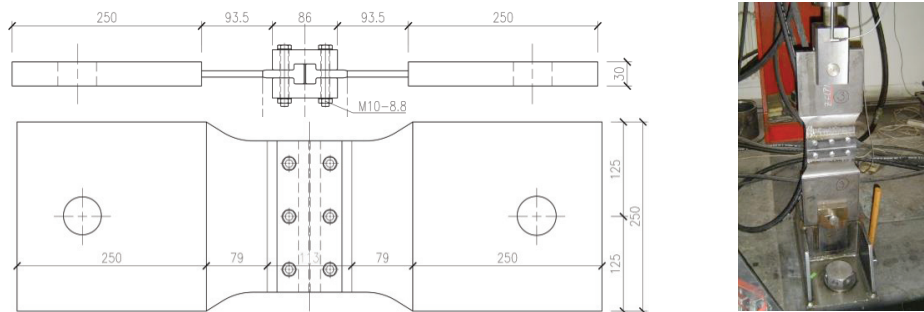


Fig. 7. Connection of railway bridge: principle and scheme of connection, shape and dimensions of test specimen, test specimen manufactured.

3.2. Fatigue tests of railway bridge connections

In total, 12 test specimens have been verified. For the cyclic loading, the electrohydraulic testing equipment (hydraulic cylinder) with the maximal capacity of 500kN, respectively 400kN, has been utilized. 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 changed in the range given by the value of the minimal force F_{\min} , from which the force was cyclically changed up to the value of the maximal force F_{\max} . Then, the loading force amplitude ΔF is given by the difference $\Delta F = F_{\max} - F_{\min}$. The loading frequency has been determined as $f = 5$ Hz. The cyclic loading has been realized up to the failure of test specimens, to which the maximal reached number of cycles N corresponds.

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 (Fig. 8a) which occurred in 9 cases. In further cases other particular failure mechanisms occurred: fracture of the plate in transition to the head (Fig. 8b), bolt fracture, weld fracture (Fig. 8c). In some tests 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 occurred. In one special untypical case the hydraulic cylinder has been damaged. These problems have been caused by the constant repetition of high-cyclic loading during fatigue tests of particular test specimens. Loading parameters only for 9 tests with typical failure mode, are listed in Table 3 – for more see [1].

The relationship between stress amplitude and number of cycles is drawn in Fig. 9. From the equation of for stress amplitude (Fig. 9a), the stress amplitude corresponding to the reference number of 2 millions loading cycles has been derived as $\Delta\sigma = 172.7$ MPa.

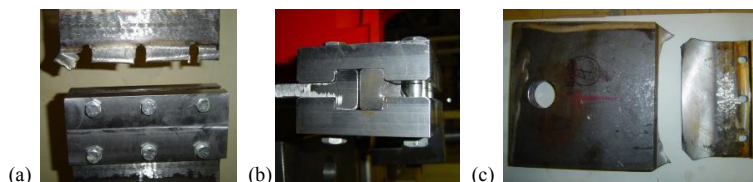


Fig. 8. Connections of railway bridge – failures: (a) plate fracture in place of bolt holes; (b) plate fracture in transition to head; (c) weld fracture.

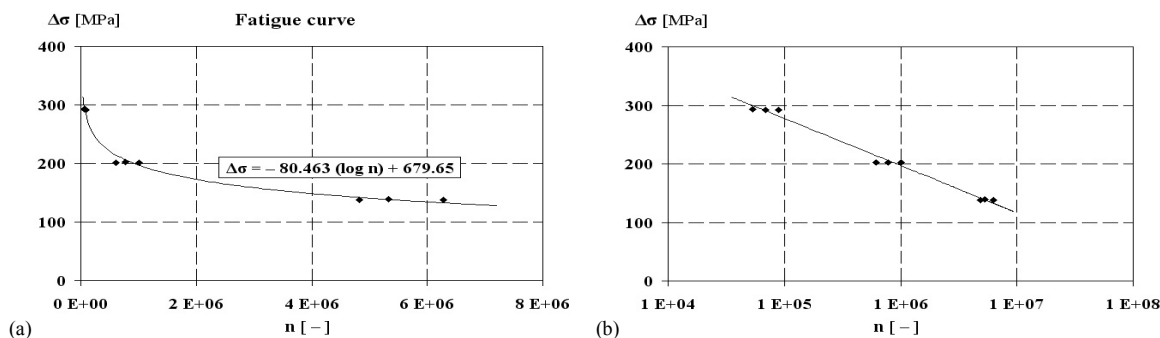


Fig. 9. Connection of railway bridge – relationships between number of cycles and stress amplitude: (a) linear scale; (b) logarithmic scale.

Table 3. Railway bridge connections – fatigue tests results: typical failure mode – plate fracture in bolt holes

Test specimens	Force amplitude ΔF [kN]	Number of cycles N
2 a	481	53 200
2 b	480	69 120
3	479	88 600
5 b	229	5 321 000
6 b	331	1 014 000
7 a	332	774 000
7 b	331	609 550
11	227	4 822 000
12	227	6 280 000

4. Probabilistic determination of fatigue strength

The determination of fatigue strength has been done according to the methodology elaborated in Annex L of the Czech Standard ČSN 73 1401 [9]. 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 (or probabilistic, respectively) evaluation aimed to the determination of the difference of extremes of the loading force of one cycle ΔF_C on fatigue limit, when constant amplitude, defined for 2 million cycles.

The procedure [for more applications see 1, 3, 4] 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 ΔF_P for $N_C = 2 \cdot 10^6$; left-prediction limit F_P (respectively $\log F_P$); the difference of loading force extremes of one cycle ΔF 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 ($x_i = \log \Delta F_i$) and the dependent variable is the logarithm of the number of cycles ($y_i = \log N_i$), is expressed by the equation

$$y = \alpha + \beta x, \quad (1)$$

$$\text{where } \beta = S_{xy} / S_{xx}, \quad \alpha = (\sum y_i - \beta \sum x_i) / n, \quad (2)$$

$$S_{xx} = \sum (x_i^2) - (\sum x_i)^2 / n, \quad S_{yy} = \sum (y_i^2) - (\sum y_i)^2 / n, \quad S_{xy} = \sum (x_i y_i) - [(\sum x_i)(\sum y_i)] / n \quad (3)$$

and n 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 and the left-prediction limit for the difference ΔF_P are

$$\Delta F_P = (2 \cdot 10^6 / 10^\alpha)^{1/\beta}, \quad \log F_P = \log (2 \cdot 10^6) - t \cdot s_R \cdot \sqrt{f}, \quad (4)$$

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

$$s_R = [1/(n-2) \cdot (S_{yy} - \beta \cdot S_{xy})]^{1/2}, \quad f = 1 + 1/n + (\log \Delta n_P - \sum x_i/n)^2 / S_{xx}. \quad (5)$$

The difference of loading force extremes of one cycle on fatigue limit for 2 million cycles is

$$\Delta F_C = \Delta F_P (2 \cdot 10^6 / N_P)^{1/\beta}. \quad (6)$$

In the case of *connections of the short footbridge*, 10 results have been evaluated. Relationships between the number of cycles and stress amplitude are shown in Fig. 4 and fatigue parameters are listed in Table 1. Applying the procedure described above, the category of the fatigue detail has been derived as $\Delta \sigma_C = 43 \text{ MPa}$.

In the case of *connections of the long footbridge*, the determination of fatigue detail category is shown using the example of the pins. The total number of the tests performed was 7 only; fatigue parameters are listed in Table 2 and the relationship between number of cycles and stress amplitude is shown in Fig. 6. Applying the procedure above, the resulting category of the fatigue detail has been derived as $\Delta \tau_C = 30.1 \text{ MPa}$.

In the case of *connections of the railway bridge*, the experimental results have been obtained from 9 fatigue tests and they are summarily listed in Table 3 and graphically expressed in Fig. 9. The stress amplitude derived using the procedure above is $\Delta \sigma_C = 153.5 \text{ MPa}$, so it is possible to assign the detail category 140, in accordance with [12].

Conclusions

Particular conclusions deduced from the test results, have been mentioned in the relevant text parts above – see paragraphs 2.3., 2.4., 3.2. The results of the experimental verification and their subsequent evaluation shown, that the structural details designed and developed during the project solution exhibit the high fatigue life, among others also in comparison with fatigue life of the structural details, which are usually used for conventional steel structures.

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