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FATIGUE ASSESSMENT OF THE PANEL PINS OF A BAILEY-TYPE ROAD BRIDGE

George N. Stamatopoulos

Educational staff at Hellenic Army Corps of Engineers
e-mail: gstamatopoulos@ath.forthnet.gr

ABSTRACT: The Bailey bridge is a space truss structure composed entirely from prefabricated panels which are assembled in situ by placing pins through the holes of the lugs at the ends of the panels' chords. The present paper deals with the fatigue assessment of these panel pins. The bridge is modelled as 3D space truss using beam elements and the Fatigue Load Model 3 (FLM 3) is chosen to verify the fatigue life of the pin detail. The model is analysed using both static and dynamic analyses and the range of the shear stresses on the pin are calculated. Finally, following the λ-method, recommended in EN 1993-2: 9.5.2, the fatigue strength of the pin is checked.

KEYWORDS: Bailey bridge, Fatigue load model, Fatigue verification for shear connectors.

1 INTRODUCTION

The Bailey bridge is a portable prefabricated structure with many important features such as easy transfer, rapid assembly and adaptability to the requirements of the construction site. Also, the Bailey bridge has the advantage that it requires no special tools and heavy equipment for its construction. The steel elements that constitute the bridge are standardized light-steel panels, easy carried by trucks and erected using manpower alone. The main beams of the bridge are composed of these prefabricated panels linked with bolts and pins.

In the present paper, the fatigue strength of these individual prefabricated segments connecting pins is examined. For this purpose, a simple bridge space truss of total length 30.48 m long is selected. The main girders are two trusses 4.549 m high and 5.867 m apart, consisting of the prefabricated panels connected with pins.

The bridge is modeled as 3D space truss using beam elements and analyzed for loading of the Fatigue Load Model 3 (FLM 3) performing both static and dynamic analyses. The shear stress range caused by the moving load on the pin detail under investigation are calculated and thereafter the simplified λ-method is used in order to verify that the calculated shear stress range is equal to or less than the fatigue strength of the pin detail. The analytical procedure is depicted in the flowchart of Fig. 1.

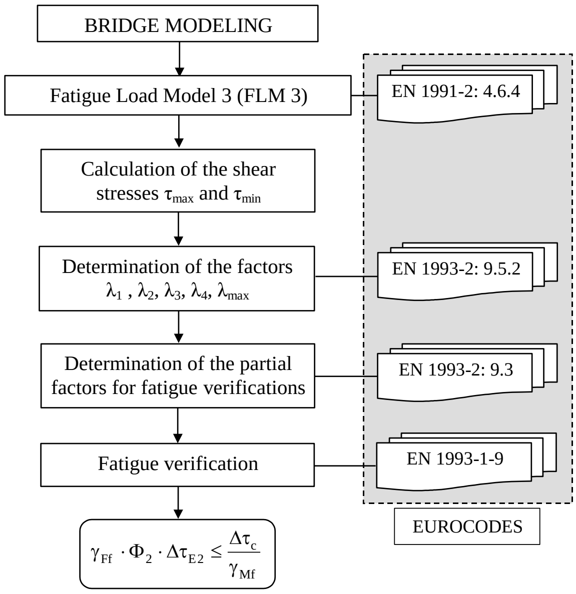


Figure 1. Flowchart of the procedure for the fatigue verification of the pin

2 BRIDGE DESCRIPTION AND MODELLING

The bridge was modeled as 3D space truss using beam elements (Fig. 2). The bridge space truss has total length 30.48 m with two main girders-trusses 4.549 m high and 5.867 m apart, consisting of prefabricated panels linked with pins.

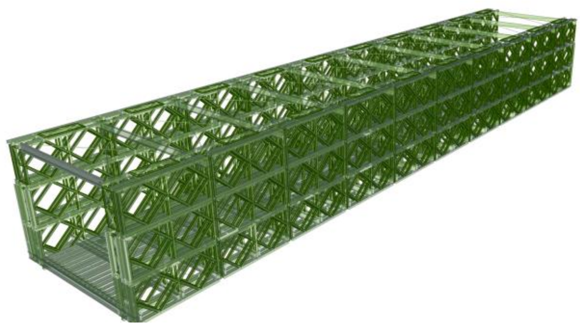
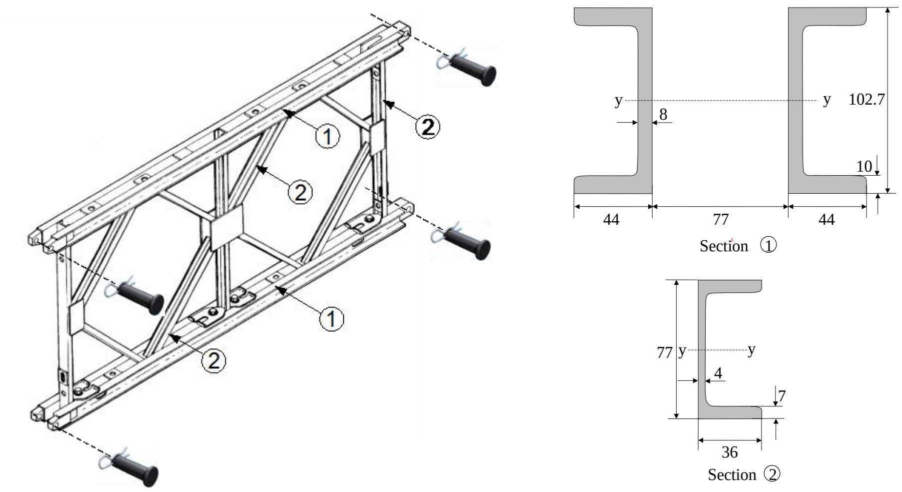


Figure 2. Finite element model of the bridge

The prefabricated panels are constructed with standard dimensions 3.048 m length and 1.55 m high, as shown in Fig. 3a. The sections of the members of the panels are depicted in Fig. 3b.



(a) (b)

Figure 3. Typical panel of the bridge with chord bolts (a) and the corresponding sections (b)

The material of the bridge is BS 968 steel grade with properties shown in Table 1. Besides, the fatigue strength of the pin detail was classified to detail category 100 of EN 1993-1-9.

Table 1. Properties for structural steel

Material	E (elasticity modulus)	f_y (yield stress)	f_u (failure stress)
Steel BS 968	[kN/cm^2]	[kN/cm^2]	[kN/cm^2]
	20680	34.4	54.0

3 FATIGUE LOAD MODEL

The Fatigue Load Model 3 (FLM 3), recommended in EN 1991-2: 4.6.4, was chosen to verify the fatigue life of the pin detail. This model is used with the simplified λ-method, in order to verify that the calculated shear stress range is equal to or less than the fatigue strength of the detail under investigation. The load model consists of a single vehicle with four axles of 120kN each. The geometry of the vehicle is depicted in Fig. 4a, while its position in the transversal direction of the bridge is shown in Fig. 4b.

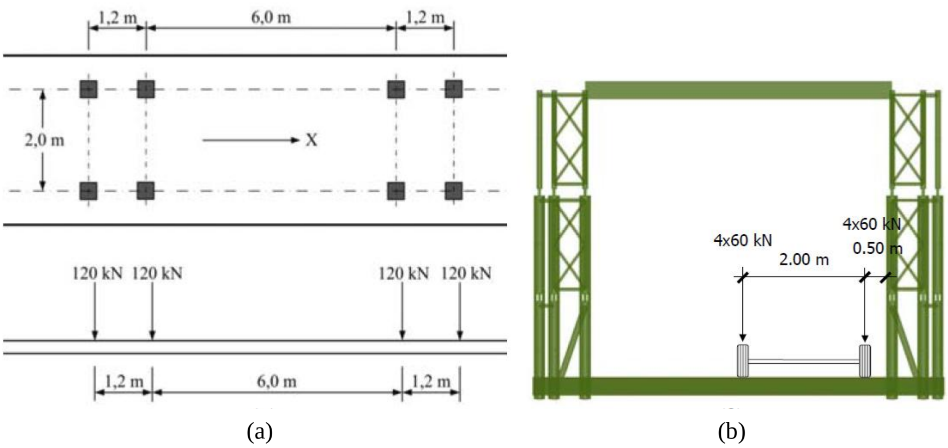


Figure 4. Load model FLM3 (axle loads 120 kN) (a) and position of FLM 3 in the transversal direction of the bridge (b)

4 STATIC ANALYSIS OF THE BRIDGE

Initially, a static analysis of the bridge was performed by applying the Load model FLM3 on five specific positions (Fig. 5, locations F_i) along the length of the bridge. For each position of the load (F_i), the corresponding components of the horizontal and vertical shear forces developed on the pins of the positions 1 and 2 were calculated and shown in Table 2.

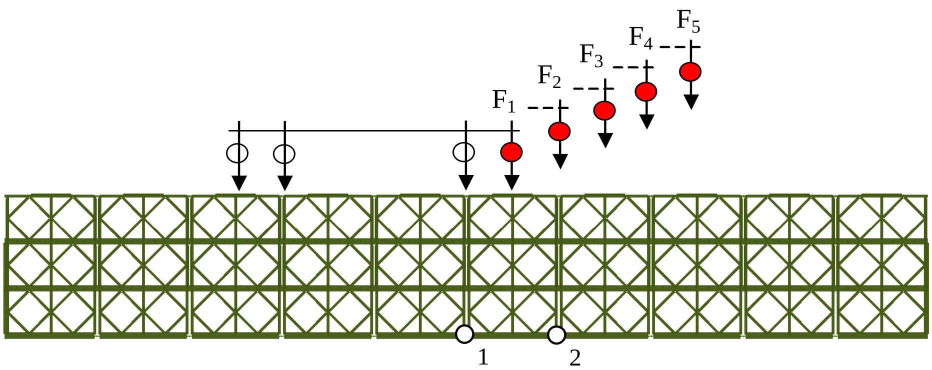


Figure 5. Positions of the Fatigue load model along the bridge considered for the static analysis

From the results of static analyses of Table 2 it can be easily obtained that loading F_1 is the worst loading case leading to the maximum shear force of the pin at position 1 (middle of the bridge), equal to $V_{tot,stat}$=160.31 kN (Fig. 6).

Table 2. Shear forces on the pins at positions 1, 2 for the loading cases F_1 to F_5

	PIN at position 1			PIN at position 2		
LOADING CASE	V_1 [kN]	V_2 [kN]	$V_{tot,stat}$ [kN]	V_1 [kN]	V_2 [kN]	$V_{tot,stat}$ [kN]
F_1	159.72	13.70	**160.31**	115.88	18.69	115.87
F_2	130.25	7.54	130.47	155.96	26.18	158.15
F_3	120.49	0.05	120.49	159.10	15.37	159.84
F_4	130.17	7.41	130.38	128.00	7.29	128.21
F_5	159.66	13.52	160.30	114.46	2.53	114.49

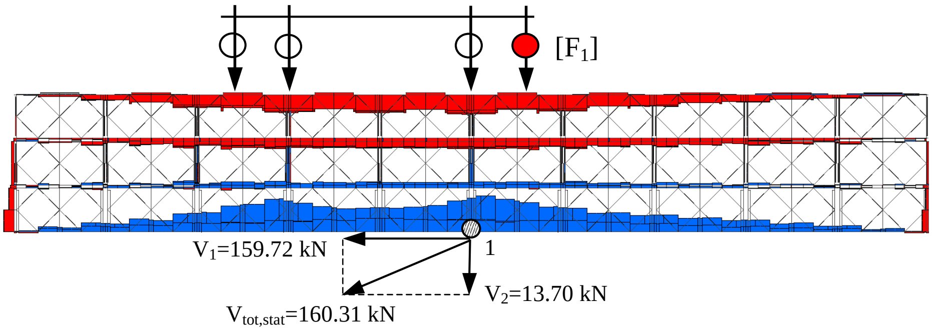
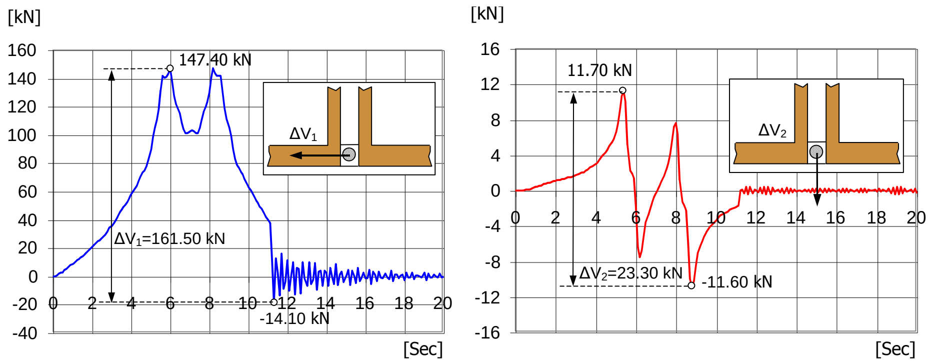


Figure 6. Position of the loading model FLM 3 (F_1) for the maximum shear force of the pin at position 1 (middle of the bridge)

5 DYNAMIC ANALYSIS OF THE BRIDGE

In a second stage, a dynamic analysis of the bridge was performed with the Load model FLM3 moving along the bridge with velocity V=10 Km/h. The variation of both horizontal and vertical shear force components over the time are shown in Figure 7a and 7b respectively, whilst the maximum shear force on the pin appears when the leading axle of the moving load is 16.68 m far away from the starting point, in other words 6 sec after starting of the loading (Fig. 8).



(a) (b)

Figure 7. Variation of the horizontal component (a) and the vertical component (b) of the shear force versus time, on the pin in the middle of the bridge

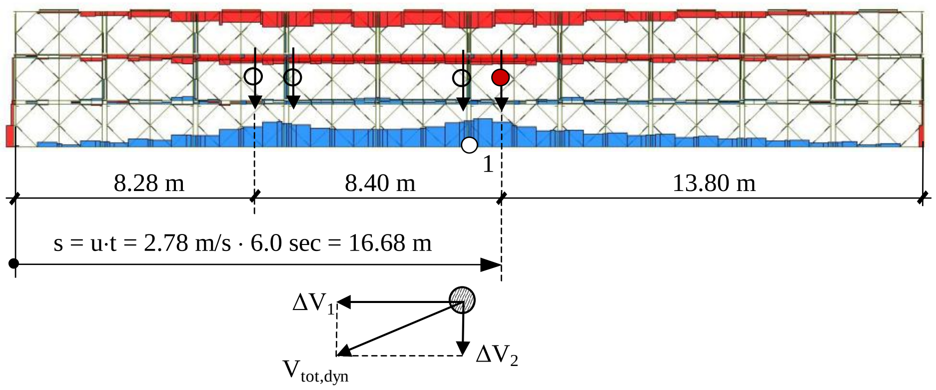


Figure 8. Position of the moving load FLM 3 leading to the maximum shear force of the pin at position 1 (middle of the bridge)

From Fig. 7a, the range of the horizontal shear component is obtained equal to ΔV_1=161.50 kN, while the vertical shear component is ΔV_2=23.30 kN (Fig. 7b). Therefore, the total shear force acting on the pin in the middle of the bridge (Fig. 8) is $V_{tot,dyn}$=163.17 kN.

Finally, the range of shear stress $\Delta\tau$ due to fatigue loading, related to the cross-sectional area of the shank of the pin $A=\pi d^2/4$ in double shear, with d= 44 mm the diameter of the shank, is obtained:

$$\Delta\tau = \frac{V_{tot,dyn}}{2\cdot A} = \frac{163.17}{2\cdot 15.2} = 5.37\ \mathrm{kN/cm^2} \qquad (1)$$

6 FATIGUE VERIFICATION FOR THE CHORD PIN

The fatigue assessment of the chord pin is obtained by checking the verification of the criterion:

$$\gamma_{Ff} \cdot \Phi_2 \cdot \Delta\tau_{E2} \leq \frac{\Delta\tau_c}{\gamma_{Mf}} \tag{2}$$

where $\Delta\tau_C$ is the reference value of fatigue strength at $N_C = 2 \cdot 10^6$ cycles, Φ_2 is a damage equivalent impact factor (Φ_2=1.00 for road bridges) and $\Delta\tau_{E,2}$ is the equivalent constant range of shear stress for two million cycles given by (EN-1994-2, 6.8.6.2(1)):

$$\Delta\tau_{E,2} = \lambda \cdot \Delta\tau \tag{3}$$

where: λ is the damage equivalence factor for road bridges

$\Delta\tau$ is the range of shear stress due to fatigue loading (as calculated from relation 1)

According to EN 1993-2: 9.5.2, the damage equivalence factor λ for road bridges up to 80 m span should be obtained from the relation:

$$\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 \leq \lambda_{max} \tag{4}$$

where λ_1 is the factor for the damage effect of traffic and depends on the length of the critical influence line or area,

λ_2 is the factor for the traffic volume,

λ_3 is the factor for the design life of the bridge,

λ_4 is the factor for the traffic on other lanes,

λ_{max} is the maximum λ-value taking account of the fatigue limit.

6.1 Determination of the factors λ_1 and λ_{max}

According to EN 1993-2: 9.5.2, the factor λ_1, should be obtained from Fig. 9a. For bridge length L=30.48 m, the factor λ_1 is calculated:

$$\lambda_1 = 2.55 - 0.7 \cdot \frac{L-10}{70} = 2.55 - 0.7 \cdot \frac{30.48-10}{70} = 2.345 \tag{5}$$

Moreover, the factor λ_{max} is taken from Fig. 9b. Thus, for the bridge under examination with length L=30.48 m, the factor is derived equal to:

$$\lambda_{max}=2.00 \tag{6}$$

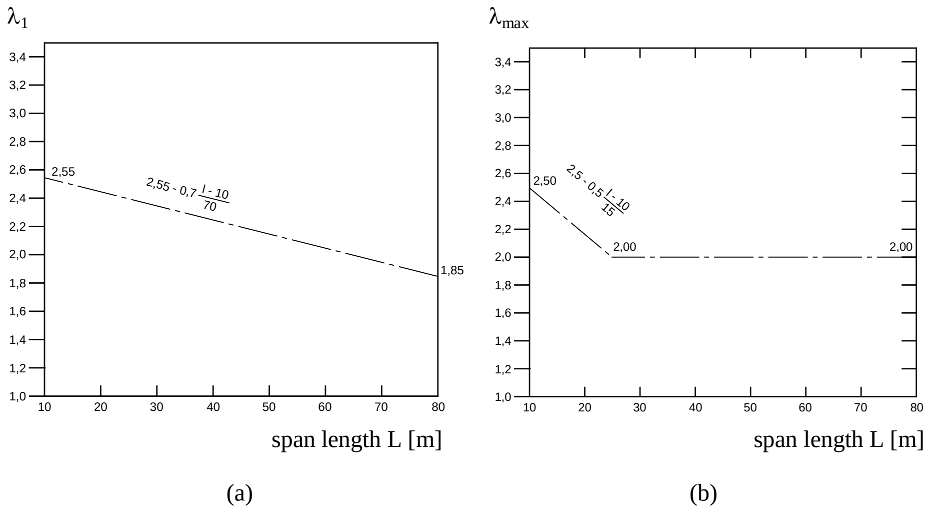


Figure 9. Factor λ_1 (a) and factor λ_{max} (b) for moments for road bridges

6.2 Determination of the factor λ_2

The factor λ_2 is the coefficient that takes into account of the annual traffic flow, calculated as follows:

$$\lambda_2 = \frac{Q_{m1}}{Q_0} \left(\frac{N_{Obs}}{N_0} \right)^{1/5} \tag{7}$$

where Q_{m1} is the average gross weight (kN) of the lorries in the slow lane obtained from:

$$Q_{m1} = \left(\frac{\sum n_i Q_i^5}{\sum n_i} \right)^{1/5} \tag{8}$$

with $Q_0 = 480$ kN

$N_0 = 0.5 \times 10^6$

N_{Obs} is the total number of lorries per year in the slow lane, defined in Table 3,

Q_i is the gross weight in kN of the lorry i in the slow lane,

n_i is the number of lorries of gross weight Q_i in the slow lane as specified by the competent authority.

Table 3. Number of expected lorries per year for a single lane

Traffic Category		Number of heavy vehicles N_{obs} per year (slow lane traffic)
1	2-Lane Highways with a high rate of heavy vehicles	2.0×10^6
2	Highways and roads with a medium rate of heavy vehicles	0.5×10^6
3	Main roads with a low rate of heavy vehicles	0.125×10^6
4	Country roads with a low rate of heavy vehicles	0.05×10^6

In the present case is $Q_i = Q_0 = 480$ kN (vehicle FLM3 with four axles of 120kN each) and $n_i = 1$. Therefore, relation (8) becomes:

$$Q_{m1} = Q_i = 480 \text{ kN} \tag{9}$$

Moreover, for local roads with a low rate of heavy vehicles, the N_{Obs} value is obtained from Table 3 equal to:

$$N_{Obs} = 0.05 \times 10^6 \tag{10}$$

By introducing relations (9) and (10) into (7), the coefficient λ_2 is derived:

$$\lambda_2 = \frac{Q_{m1}}{Q_0}\left(\frac{N_{Obs}}{N_0}\right)^{1/5} = \frac{480}{480}\left(\frac{0.05 \cdot 10^6}{0.5 \cdot 10^6}\right)^{1/5} = 0.63 \tag{11}$$

6.3 Determination of the factor λ_3

The factor λ_3 is given from the relation:

$$\lambda_3 = \left(\frac{t_{Ld}}{100}\right)^{1/5} \tag{12}$$

where t_{Ld} is the design life of the bridge in years (Table 4).

Table 4. Factor λ_3

Design life of the bridge in years	50	60	70	80	90	100	120
Factor λ_3	0.871	0.903	0.931	0.956	0.979	1.000	1.037

From the above Table 4, for design working life equal to 50 years, the corresponding factor λ_3 is obtained:

$$\lambda_3 = 0.871 \tag{13}$$

6.4 Determination of the factor λ_4

The λ_4 factor is calculated from the relation:

$$\lambda_4 = \left[1 + \frac{N_2}{N_1}\left(\frac{\eta_2 Q_{m2}}{\eta_1 Q_{m1}}\right)^5 + \frac{N_3}{N_1}\left(\frac{\eta_3 Q_{m3}}{\eta_1 Q_{m1}}\right)^5 + \cdots + \frac{N_k}{N_1}\left(\frac{\eta_k Q_{mk}}{\eta_1 Q_{m1}}\right)^5\right]^{1/5} \quad (14)$$

where k is the number of lanes with heavy traffic,
N_j is the number of lorries per year in lane j,
Q_{mj} is the average gross weight of the lorries in lane j,
η_j is the value of the influence line for the internal force that produces the stress range in the middle of lane j.

Due to the fact that in the present case the bridge has only one traffic lane, the coefficient λ_4 is:

$$\lambda_4 = 1.00 \quad (15)$$

Finally, the damage equivalence factor λ (relation 4) becomes:

$$\lambda = \lambda_1 \cdot \lambda_2 \cdot \lambda_3 \cdot \lambda_4 = 1.287 < 2.00 \quad (16)$$

6.5 Calculation of the equivalent constant amplitude stress range $\Delta\tau_{E,2}$

Introducing the calculated values of λ and $\Delta\tau$ (from relations 16 and 1) into relation 3, the equivalent constant amplitude stress range, related to 2 million cycles, is calculated:

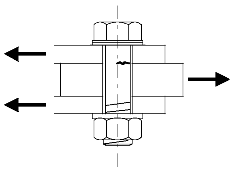
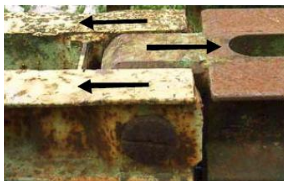
$$\Delta\tau_{E,2} = \lambda \cdot \Delta\tau = 1.287 \cdot 5.37\ \text{kN/cm}^2 = 6.92\ \text{kN/cm}^2 \quad (17)$$

6.6 Classification of steel fatigue detail

The pin joint is in double shear and can be classified as 100 MPa, according to detail of Table 5 (Table 8.1 of EN1993-1-9). Therefore, the reference value of the fatigue strength at N_C = 2 million cycles, is:

$$\Delta\tau_C = 100\ \text{N/mm}^2 = 10\ \text{kN/cm}^2 \quad (18)$$

Table 5. Constructional detail

Detail category	Constructional detail	Description	Photo of the joint
100 m=5		Bolts in single or double shear Thread not in the shear plane	

6.7 Determination of the partial factors for fatigue verifications

The partial factor for fatigue strength γ_{Mf} is defined from Table 6 (recommended values given in EN-1993-2, 3). For safe life assessment method with high consequences of the chord bolt failure on the bridge, γ_{Mf} =1.35.

Table 6. Recommended values for partial factors for fatigue strength

Assessment method	Consequence of failure	
	Low consequence	High consequence
Damage tolerant	1.00	1.15
Safe life	1.15	1.35

Moreover, the fatigue partial factor γ_{Ff} is taken γ_{Ff} = 1.00, as recommended in EN-1993-2, 9.3.

6.8 Fatigue verification of the pin

The calculated values of the fatigue partial factor γ_{Ff} = 1.00, the equivalent constant range of shear stress for 2 millions cycles $\Delta\tau_{E,2}$=6.92 kN/cm², the reference value of fatigue strength at 2 million cycles $\Delta\tau_C$=10 kN/cm² and the partial factor for verification of pins in bridges γ_{Mf} =1.35, are introduced into relation (2):

$$\gamma_{Ff}\Phi_2\Delta\tau_{E2} = 1.00 \cdot 1.00 \cdot 6.92 = 6.92 \text{ kN/cm}^2 < \frac{\Delta\tau_c}{\gamma_{Mf}} = \frac{10.0}{1.35} = 7.40 \text{ kN/cm}^2 \quad (19)$$

Therefore the pin is sufficient against fatigue loading.

7 CONCLUSIONS

In the present paper the fatigue assessment of the panel pins of a Bailey bridge was examined. The bridge was modelled as 3D space truss using beam elements and the Fatigue Load Model 3 (FLM 3) was chosen to verify the fatigue life of the pin detail. The model was analysed using both static and dynamic analyses and the range of the shear stresses on the pin were calculated. Finally, following the λ-method, recommended in EN 1993-2: 9.5.2, the fatigue strength of the pin was checked and found being sufficient against fatigue loading.

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