FATIGUE OF LOCKED COIL ROPES DUE TO BENDING

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SUMMARY

The article concerns a research project, in which the application possibilities of locked coil ropes as rope hangers in tied arch bridges were examined. Particular attention was placed on the effect of bending in the transition zone of the end anchorage into the free rope length. The article presents not only the central results of the part tests, but as a conclusion, it also presents a possible practical procedure for providing a proof of the applicability, or rather the fatigue limit of rope hangers under bending stress.

Keywords: *Tied arch bridges, fatigue, rope hangers, locked coil ropes, bending stress.*

1. GENERAL INTRODUCTION

Ropes have become established as a reliable design feature for the transmission of tensile forces in structural engineering. For this purpose their dimensioning is comprehensively regulated in the current standards. Due to oscillations, changes of wire sag or also through deformations in the anchorage area caused by traffic, additional bending stress can however arise in ropes, which can currently not be evaluated on the basis of normative specifications.

The occurrence of such strains is often countered with constructional measures: such as the installation of vibration dampers or guying. If such measures are not possible or not wanted (e.g. for maintenance reasons), but according to the concept the occurrence of alternating stresses caused by traffic and wind has to be considered, then there are often insecurities in planning: with regard to their technical suitability, time delays in the approval process, costs caused by possible part tests, etc.

Rope hangers in tied arch bridges are one area of application where particular attention has to be paid to a fatigue-resistant design. In order to examine the applicability of ropes in this type of bridge, the Federal Waterways Engineering and Research Institute (BAW) in Karlsruhe initiated a research project [1], the results of which will be reported on in the following.

There is indeed a great variety of different constructions in pedestrian and cyclist bridges which confirm the general suitability of ropes within this area. Also technical advantages with dynamic aspects lead again and again to their usage (among other things the wilful excitation of vibrations in hangers, see [2]). The requirements, which result from traffic and the related variable stresses relevant for fatigue, make it currently difficult however, to implement rope hangers in bridge construction more frequently.

The content of the research project was in part fundamental investigations of the load bearing and fatigue behaviour of locked coil ropes under bending stress in the zone near the anchorage. The other objective was to enable the actual exchange of damaged hangers on an existing road bridge with ropes on the basis of tests on construction parts as well as to develop a practical design method for the future use of rope hangers.

2. INTRODUCTION TO THE TOPIC

Currently in Germany full locked coil ropes are predominantly used in bridge constructions with road traffic. The special feature of this type of rope, which the investigations described are restricted to, is the combined structure of the cross section consisting of round wires and Z-shaped wires (partial image left in Fig. 1).

Due to the large difference in rigidity, the rope transition point, where the rope leaves the metallically cast rope socket, is the relevant area with regard to fatigue bending stress (partial image right in Fig. 1).

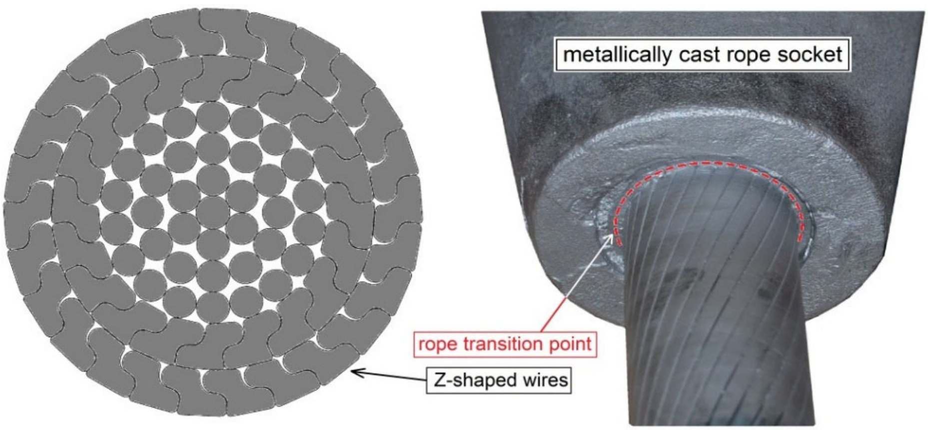


Fig. 1. *Full locked coil rope: cross section and rope transition point at the anchorage.*

Fatigue relevant stresses from traffic are usually determined in a calculation applying the fatigue load model LM3 according to DIN EN 1993-2 (crossing of a 48 ton vehicle). To determine the governing stress in the area of the hanger connection, all deformation components and the influence of the normal forces in the hangers are to be considered. Explanations concerning the procedure and the particularities of elements bearing tensile forces can be found amongst others in [3].

Fig. 2 shows the deformation and stress curves arising in this case in an example bridge construction (Gelmer Brücke). Regarding the occurrence of fatigue relevant bending stress in the area of the hanger connection, the longer hangers in the middle of the bridge construction (here: hanger 5) are relevant.

The total stress consists of normal force and bending proportions, whereby the former has approximately the shape of half a sinusoidal wave. Their maximum is reached when the vehicle is in the area of the hanger investigated. The stress proportions which are caused by the deformation however have the shape of a complete sinusoidal wave during the crossing of the vehicle, so compared to the normal force they occur approximately at double frequency.

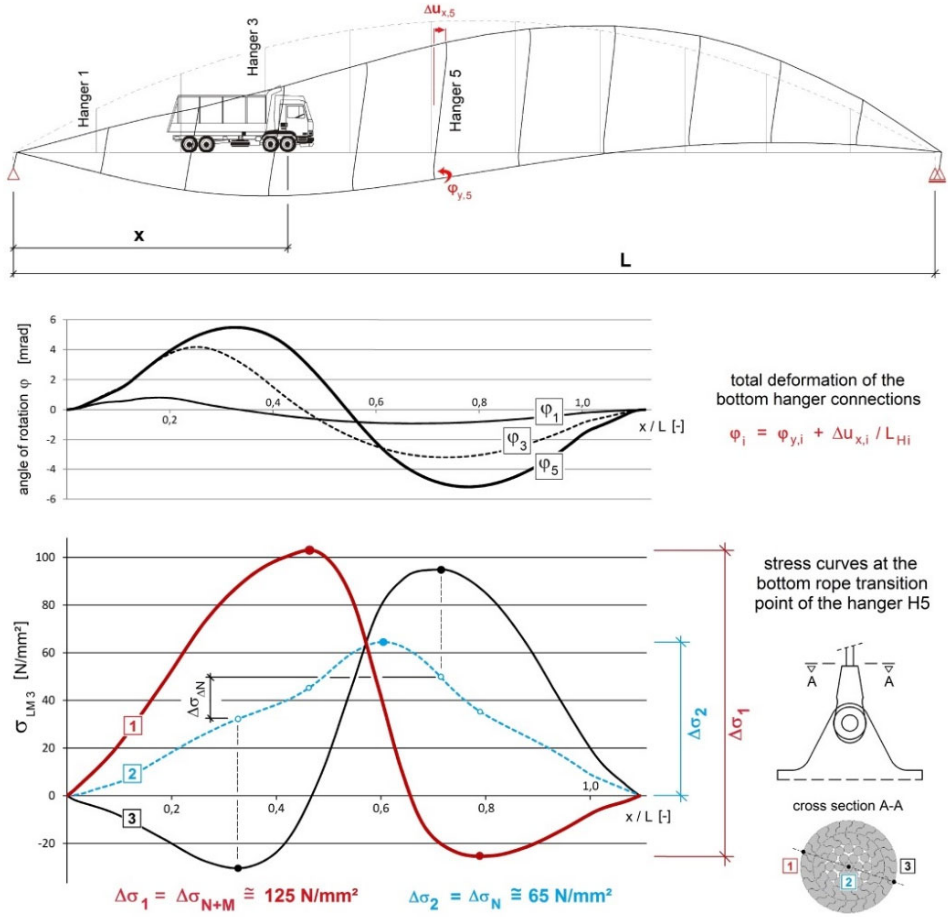


Fig. 2. Deformations and stresses in the hanger connection area under LM3.

The stresses determined refer to the rope transition point. The calculation is based initially on a constant rope rigidity over the length of the hanger and on a simple determination of stress in the circular / rope cross section.
It was presumed that it is possible for the bending moment that arises in the rope anchorage to be transmitted into the rope. This presumption is generally on the safe side, but it is justifiable in the scope of the present examinations even with "hinged" fork sockets with bolt connection:

- "small" fatigue relevant deformations and/or alternating stresses are examined,

- the bolt connection is not frictionless in reality (rather more friction can be expected in the long term in the contact area: due to damage to the corrosion protection causedduring assembly in connection with high local compression, due to moisture / de-icing salt in areas which are difficult to access/repair),
- transverse to the "hinged" axis a transmission of moments is possible: over the width of the gusset plate or rather the spreading of the connection lug.

The normative specified limit value in Germany for the proof of fatigue resistance of locked coil ropes according to DIN EN 1993-1-11 in connection with the national appendix is $\Delta\sigma_c$ = 112 N/mm². This value presupposes alternating stresses caused by normal forces in the rope and therefore includes only the proportion that is shown in blue in Fig. 2 with approx. 65 N/mm². Under consideration of the additional bending proportions however, the load range almost doubles close to the anchorage of the rope and reaches approximately 125 N/mm². This example shows that, under application of the normative limit value – for the time being without consideration of the partial safety factors and λ-factors – an evaluation of the stresses is neither possible in terms of content nor is it possible in terms of the amount of the load.

3. PROCEDURE

As there was only very little information to be found in technical literature, which was directly applicable to the issue examined in this paper, in the scope of this research project two test series were designed and conducted for the examination of altogether 18 full locked coil ropes in the diameter range between 21 and 45 mm. Prior to the tests, the test conditions had been derived from the normative and technical requirements concerning rope hangers in tied arch bridges carrying traffic.

In the investigations, special attention was paid to the realistic simulation of the stress cycles at the rope transition point. In the first test series conducted at the Technical University of Munich this led to a decoupled control of the normal forces and the bending stresses with a frequency ratio of 1:2 (see Fig. 2). The angular rotation was accomplished by tipping the upper anchoring block, which was assembled with a hinge. Fig. 3 shows the principle of the test set-up and the function of the two control cylinders (light blue and dark blue arrows).

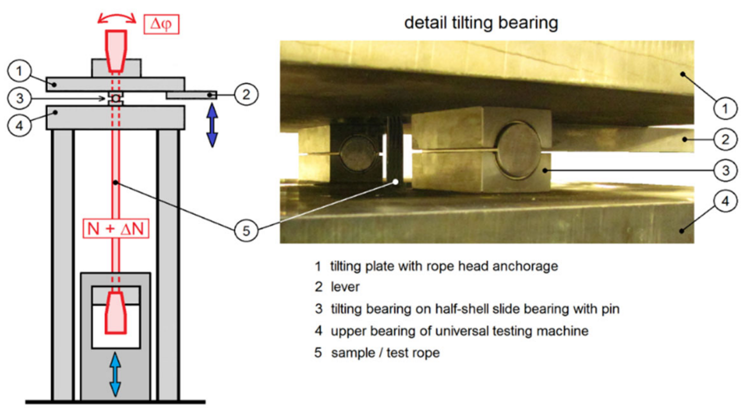


Fig. 3. *Test set-up at the Technical University of Munich.*

In order to simplify the test procedure and to obtain analogue results at both rope heads, a centred transverse deflection was chosen for the second test series, which was conducted at the Technical University of Brunswick.

Parallel to the part tests a structure model was developed, which can represent a section of the rope with its stranded single wires and the associated contact conditions between the wires. By means of the model it was possible to gain important insights into the load bearing behaviour, in particular in the area where the rope exits the rope socket. Owing to a calibration using published test results and own measurements the model also served for the definition of the test conditions as well as for the computed evaluation of further types of rope.

4. EVALUATION OF THE TEST SERIES

The central concern of the investigations was the identification and description of the relevant mechanisms of damage, which cause the first cracks and therefore limit the life span of the rope under alternating normal force and bending.

The evaluation of the test results led to the conclusion that in particular influences due to contact between the outermost wires and the casting material are to be regarded as life span determining. The mechanism associated with this is known as fretting corrosion. It arises when two friction partners under transverse pressure are subjected to alternating longitudinal forces and are therefore subjected to minimally oscillating relative movement. This leads to damages in the contact area, which resemble mechanical wear, resulting in roughening and damage to the surface. As a result, the fatigue limit of the elements involved (e.g. rope wires) decreases significantly as a function of different parameters (material hardness, degree of the relative movement, level of the transverse pressure, etc.). This mechanism of damage is well-known in ropes, also being the determining factor for the bearable rope normal force load range, which, amongst other things, causes relative movement of the contact points between the individual rope wires in the free rope length under necking pressure.

Regarding the (combined) occurrence of temporally variable rope forces and bending stresses in the end section of the rope, the following engineering model was developed for the purpose of an analytical description.

When applying a tensile rope force or already when prestretching a rope, the contraction of the rope in the area of the rope exit results in a detachment of the rope surface from the casting material. If now a temporally variable (axial) rope force ΔN is added, relative movements due to different elongation arise in the end section of the rope between the rope wires and the casting material. In the immediate entrance area of the rope into the casting material these elongation differences arise however without transverse pressure. Only inside the casting material, where the rope wires split and are transferred into what we call a wire brush, additional deviation forces and anchor forces act on the wires. Consequently, it is possible that the conditions described above and which are necessary for the occurrence of fretting corrosion can develop there – which is by tendency inside the casting material. Figure 4 illustrates these correlations qualitatively. The detachment zones are highlighted in blue, the areas with relative movement under transverse pressure are highlighted in red.

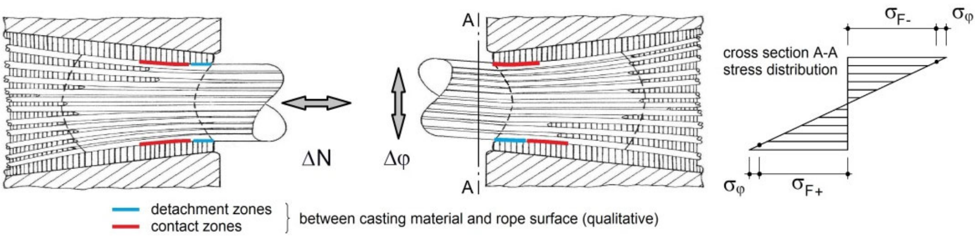


Fig. 4. *Model conception of the development of fretting corrosion under normal force and bending.*

Applying bending deformation Δφ by means of transverse deflection or torsion of the rope head in the end section of the rope (partial image right in Fig. 4) results in a different disposition of the critical contact areas. A one-sided pressure contact arises immediately at the rope transition point, resulting from the rope being pushed against the casting material. The opposite rope side however rather detaches from the casting material. In the outer wires of the rope the stress proportions from the longitudinal force (σ_F) and from local wire bending (σ_φ) overlap, because the casting material inhibits relative movements of the rope wires and therefore the rope, consisting of individual - wires, acts almost like a homogeneous circular cross section. Thus there are strains caused by both stress proportions in the bending compression zone, which result in relative movements in the casting material under transverse pressure. The unfavourable conditions for fretting corrosion occur therefore in both stress proportions. Analogue loads occur in the bending tension zone at the rope transition point however without transverse pressure. This means that conditions for fretting corrosion only develop deeper inside the casting material. It can be assumed that the value of the stresses to be considered remain limited to the proportion σ_F because the local wire bending proportion σ_φ subsides quickly in the casting material.

Figure 5 shows the inferred analytical consideration. Regarding the fatigue resistance of the rope it is recommended to solely consider the load ranges $\Delta\sigma_{F+\varphi}$, which are in direct correlation with the occurrence of life span determining conditions for fretting corrosion. The contact zone between the outer layer of wires and the casting material has been found to be the determining factor in this case. These stresses consist on the one hand of variable normal wire forces $\Delta\sigma_F$ (from rope force and/or bending) and on the other hand of the proportion of wire bending $\Delta\sigma_\varphi^-$ which occurs locally at the rope transition point. The double amplitude of stress relevant for fatigue does therefore not correspond with values that have possibly been determined through measurements on the wires ($\Delta\sigma_{DMS}$).

The final evaluation of the test results is displayed in a Woehler diagram in figure 6. Not only the test results but also the normative limit values according to DIN EN 1993-1-11 are entered in the diagram.

The test results were described in the red curve as a lower envelope curve. The definition of the curve follows the DIN EN 1993-1-11. The resulting fatigue limit at two million load cycles for combined loads in the outermost rope wires (Z-shaped wires) from normal force and bending is a value of $\Delta\sigma_{F+\varphi} = 200$ N/mm².

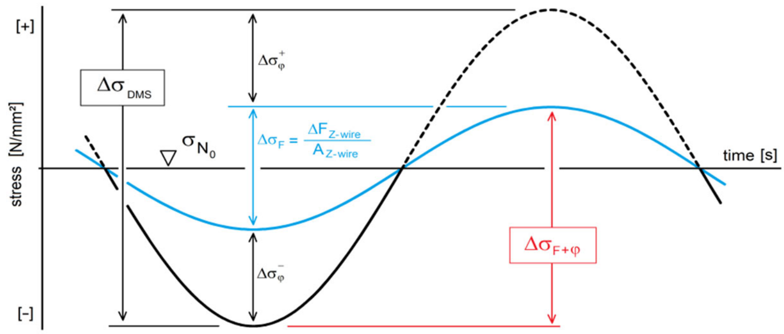


Fig. 5. Analytical evaluation of the fatigue relevant stress proportions.

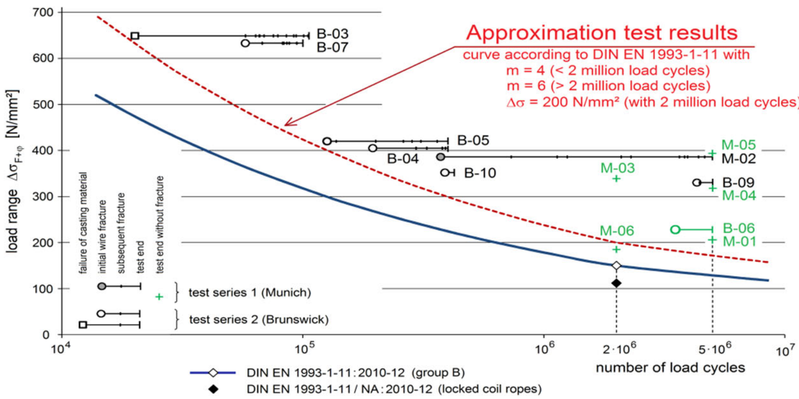


Fig. 6. Summary of the test results.

Tests considered as passed with regard to the normative requirements are entered in green colour. Within the framework of these investigations (with “smallish” rope diameters) this meant that during the fatigue test a maximum of only one wire break could occur. In view of these strict terms the application of the suggested curve within the fatigue limit range (< 2 million load cycles) cannot be recommended. The focus should rather be put on the present matter of interest, which is, to accomplish a best possible fatigue-resistant dimensioning in the design of rope hangers in tied arch bridges.

5. DEDUCTION OF A PRACTICAL PROOF PROCEDURE

The previous stress-based evaluation requires extensive and complex calculations for the determination of the wire stresses and their composition. The application of the aforementioned findings in practice would therefore require unreasonable effort.

However in order to make the evaluation of the use of ropes in tied arch bridges possible, a practical procedure has been developed. It is based on the total angle oscillation range $\Delta\varphi$ positioned directly at the rope transition point, which consists of the torsion angle at the end of the hanger and the tangent torsion of the rope hanger (see Fig. 2). Due to the minor influence of the hanger rigidity, a determination of these deformations may be carried out at the complete structure according to linear static analysis.

Fig. 7 shows the suggested limiting curve, which was determined in the scope of extensive parameter analyses. The area of application and application limits are described in this diagram.

Due to the combined load consisting of normal force and bending, it has to be proven in addition to the angle oscillation range, that the alteration of the normal force during the bending cycle remains limited to a value of $\Delta\sigma_{\Delta N} \leq 20$ N/mm² (see Fig. 2).

For the proof of fatigue resistance (at 2 million load cycles) in the area of the rope transition point the following format is recommended:

$$\gamma_{Ff} \cdot \Delta\varphi_{E2} \leq \frac{\Delta\varphi_{VVS}}{\gamma_{Mf}} \qquad (1)$$

with:

- $\Delta\varphi_{E2}$: damage-equivalent angle oscillation range related to 2 million load cycles (i.a. with application of the factor λ)
- $\Delta\varphi_{VVS}$: fatigue resistant angle oscillation range of Z-shaped wires according to Fig. 7 (related to 2 million load cycles)
- γ_{Ff}: partial safety factor for fatigue loads with $\gamma_{Ff} = 1.0$ in accordance with DIN EN 1993-2 in connection with the national appendix
- γ_{Mf}: partial safety factor on the material side with $\gamma_{Mf} = 1.0$ in accordance with DIN EN 1993-1-9, Table 3.1

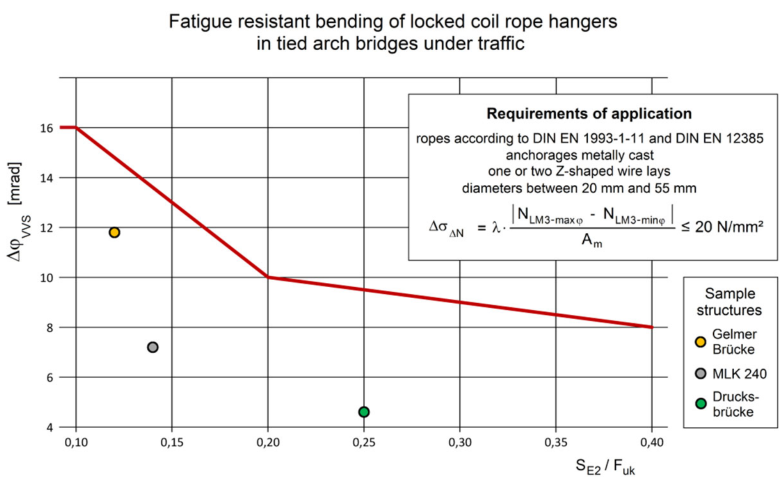


***Fig.** 7. Suggestion for the dimensioning of locked coil ropes as rope hangers in tied arch bridges.*

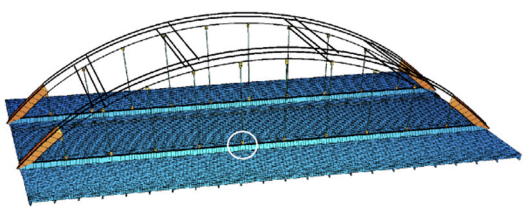
The choice of the material's partial safety factor $\gamma_{M,f}$ was based on the design concept of damage tolerance with little damage consequences. This classification was justified by the fact that,

- bridges are structures that are generally closely monitored,
- rope transition points are accessible and examinable,
- bending related initial fractures systematically occur in the outer wires of the rope and thus are visually recognisable,
- in the context of structural safety, the possible (systematic) exchange and the sudden loss of a rope are accounted for.

6. EXEMPLARY APPLICATION OF THE PROOF PROCEDURE

The applicability of rope hangers was proven within the scope of [1] at three existing structures. The following example demonstrates the procedure for the bottom connection of a long hanger at the structure "MLK 240".

The structure is a steel tied arch bridge, which carries a two lane road. The span is approx. 67 metres. The road is positioned in the middle with two broad cycle and footpaths at either side of the road. Fig. 8 shows a view of the three dimensional model of the structure as well as a summary of the proof with its determining internal forces and deformations.



	total angle of rotation max		total angle of rotation min	
	max φ_y [mrad]	zug. φ_x [mrad]	min φ_y [mrad]	zug. φ_x [mrad]
φ_{bottom}	1,07	0,07	-1,09	-0,29
related $\varphi_{tangent}$	0,80	0,36	-0,85	-0,36
total	**1,87**	**0,43**	**-1,94**	**-0,65**
superposition	**1,92 mrad**		**2,05 mrad**	
related $S_{LM3\,\varphi}$	19 kN		11 kN	
maximal S_{LM3}	81 kN			
related $S_{g,k}$	230 kN			

Fig. 8. *Structure "MLK 240" - model of the structure and analysis results.*

In the course of the structure's preliminary design, a diameter of 45 mm for the rope hangers was determined. The characteristic value of the rope breaking force according to table B.2 in DIN EN 12385-10 amounts to F_{uk} = 1,930 kN. The metallic cross section has an area of A_m = 1,340 mm². The amount of the occurring normal force load range at the times of maximum angles of rotation is calculated by using the related damage-equivalent λ factor = λ_{max} = 1.80

$$\Delta\sigma_{\Delta N} = 1.8 \cdot (19\text{ kN} - 11\text{ kN}) / 1{,}340\text{ mm}^2 \cdot 1{,}000 = 10.8\text{ N/mm}^2 < 20\text{ N/mm}^2.$$

The applicability of the simplified procedure is therefore possible.

The input values for the simplified procedure are calculated as follows:

$$\Delta\varphi_{E2} = 1.80 \cdot (1.92 + 2.05) \approx 7.2\text{ mrad}.$$

$$S_{E2} = S_{g,k} + \lambda \cdot \max(S_{LM3\,\varphi+}; S_{LM3\,\varphi-}) = 230\text{ kN} + 1.80 \cdot 19\text{ kN} \approx 264\text{ kN}.$$

The reference value is therefore:

$S_{E2} / F_{uk} = 264 \text{ kN} / 1{,}930 \text{ kN} = 0.14.$

From Fig. 7 can now be deduced: $\Delta\varphi_{VVS} = 13.6$ mrad.

The fatigue proof for bending at the rope transition point is thus provided:

$\gamma_{Ff} \cdot \Delta\varphi_{E2} = 1.0 \cdot 7.2 \text{ mrad} = 7.2 \text{ mrad} < 13.6 \text{ mrad} = \Delta\varphi_{VVS} / 1.0$ ✓

The result of the recalculation is entered into Fig. 7 as a grey data point.

Finally, the proof for the maximum alteration of the normal force under LM 3 (which is already regulated in the standards) is provided. In the present case this value amounts to $\Delta S = \max S_{LM3} = 81$ kN. The proof is just within the allowed margins:

$$\gamma_{Ff} \cdot \Delta\sigma_{E2} = 1.0 \cdot 1.8 \cdot 81 \text{ kN} / 1{,}340 \text{ mm}^2 \cdot 1{,}000 =$$
$$= 108.8 \text{ N/mm}^2 < 112.0 \text{ N/mm}^2 = 112 \text{ N/mm}^2 / 1.00 = \Delta\sigma_{c,NA} / 1.00$$

The proof of the alteration of the normal force is therefore the overall relevant proof.

The applicability of locked coil ropes was proven at two further structures. The results of these calculations are entered as yellow and green data points in Fig. 7. At one of these structures (Gelmer bridge) works for the exchange of the damaged round steel bar hangers for rope hangers are currently being carried out.

7. CONCLUSION

In the context of a research project the capabilities of full locked coil ropes as rope hangers in tied arch bridges were investigated. As a conclusion alongside the central results, a possible practical proof procedure was presented.

ACKNOWLEDGEMENT

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