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A Preliminary Bending Fatigue Spectrum for Steel Monostrand Cables

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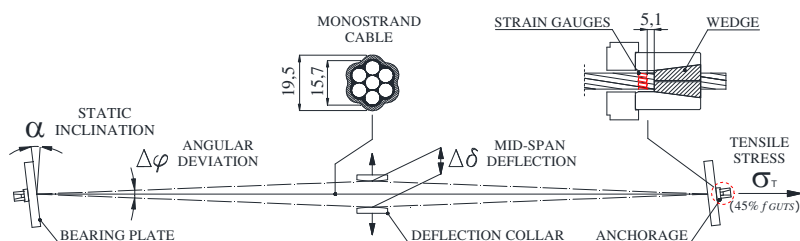
Keywords: *high-strength monostrand steel cable; bending fatigue spectrum; cyclic loading*

Large-amplitude vibrations of bridge cables have been frequently reported in the published literature. Cables with their flexibility and low structural damping are particularly susceptible to different types of vibrations that may lead to cable fatigue failures near the anchorage. Despite extensive research on the mechanisms of dynamic excitation, limited work has been undertaken to thoroughly assess the fatigue characteristics of the various types of bridge cables subjected to cyclic transverse deformations, as cables are in principle not expected to experience bending-related deformations.

Moreover, the commonly applied qualification tests for the fatigue resistance of stay cables, as outlined in *fib* and PTI, do not specifically address fatigue issues related to transverse cable vibrations and therefore do not require testing for bending. As a consequence of this, high-strength steel cable bending fatigue spectra have not yet been developed. Thus, the calculation of the fatigue lifetime of stay cables is currently only possible for axial variations in stresses.

As the majority of modern stay cables used in cable stayed structures are comprised of a number of individual high-strength steel monostrands, investigations of the bending fatigue performance of the individual monostrand have become more relevant.

To address the aforementioned deficiencies, a monostrand cable test rig that can simulate flexural effects was devised to test 5,1 m long monostrand cables under bending at a fixed axial load level (45% of ultimate tensile strength). The test rig allows for both static inclination at the anchorage α (simulating installation tolerances) and dynamic variation in deflection angle of the strand. A set of eight individual monostrand bending tests were undertaken, covering a large range of expected cable vibration amplitudes.



The angular deviation $\Delta\phi$ at the anchorage was obtained by sinusoidally varying the mid-span deflection $\Delta\delta$ of the cable (Fig.1). With this test setup, maximum bending deformations were introduced near the anchorages and the performance of the cables under bending fatigue was evaluated.

Fig. 1: Simplified model of the cable configuration

From the bending fatigue tests conducted, a preliminary S-N curve is proposed for the conservative estimation of monostrand cable service life expectancy. The presented bending fatigue spectrum of seven-wire high-strength monostrands is currently unavailable in the published literature. Moreover, the results provide relevant information on the bending mechanism and fatigue characteristics of monostrand steel cables in tension and flexure and show that localised cable bending has a pronounced influence on the fatigue resistance of bridge cables under dynamic excitations.

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Summary

This paper presents the results of the experimental study on the bending fatigue resistance of high-strength steel monostrand cables. From the fatigue tests conducted, a preliminary bending fatigue spectrum is derived for the conservative estimation of monostrand cable service life expectancy. The presented bending fatigue spectrum of high-strength monostrands is currently unavailable in the published literature. Moreover, the results provide relevant information on the bending mechanism and fatigue characteristics of monostrand steel cables in tension and flexure and show that localised cable bending has a pronounced influence on the fatigue resistance of cables under dynamic excitations.

Keywords: *high-strength monostrand steel cable; bending fatigue spectrum; cyclic loading*

1. Introduction

For many cable-stayed structures, high strength steel cables are the preferred tensile load bearing structural element as they are by far the least expensive per unit tensile force. Cable stays support many telecommunication masts, stadiums, bridges and offshore platforms. In many cases, these stays are exposed to wind, waves or water currents that can generate large amplitude vibrations both in the stays and in the supported structures. Cables with their flexibility and low structural damping are particularly susceptible to different types of vibrations that may lead to cable fatigue failures near the anchorage [1].

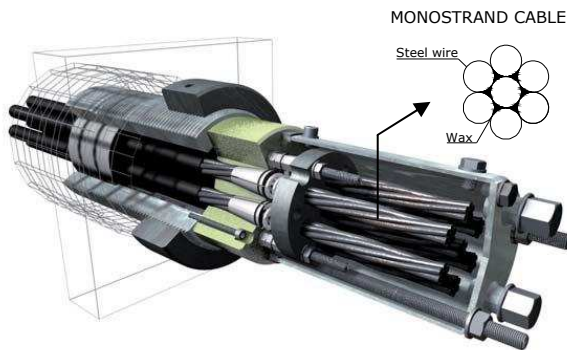
The understanding of fatigue mechanisms in most steel structures is well established. In the case of cables composed of steel wires, though, many important aspects remain to be clarified. In general, fatigue can be described as the progressive and localized structural damage that occurs when a material is subjected to cyclic loading that may produce cracks or lead to complete rupture after a certain number of fluctuations. Cables can be subjected to two different types of fatigue failures: axial fatigue and bending fatigue.

1.1 Cable fatigue damage criteria

Different criteria have been proposed in literature to evaluate cable fatigue damage. The problem of cable axial fatigue has been previously investigated [2]. A considerable contribution to the same topic [3] summarized the published axial fatigue tests and developed an axial fatigue spectrum for spiral strands. However, limited work has been undertaken to thoroughly assess the fatigue characteristics of the various types of bridge cables subjected to cyclic transverse deformations as cables are in principle not expected to experience bending. Although the problem of cable bending fatigue has also been studied [4-7], there are still unresolved issues that need clarification and some aspects of these form the basis of the present paper. It was reported that the current approaches and the fatigue models do not give sufficiently accurate results and the methods seeking to evaluate the cable's fatigue strength should be developed further to be consistent with observed fatigue failures for cables subjected to transverse deformations [8,9].

1.2 Bending fatigue tests on cables

To date, several experimental investigations of stay cable fatigue behaviour under bending have been carried out [10-12]. In most cases, bending stresses at the anchorage corresponding to the applied angular deviations were not measured.



As the majority of modern stay cables used in cable stayed structures are comprised of a number of individual high-strength steel monostrands (Fig.1), investigations of the bending fatigue performance of individual monostrand have become more relevant. The work presented in this paper specifically addresses the fatigue performance of a monostrand cables under flexural load reversals.

Fig. 1: Parallel Mono-Strand Stay Cable Anchorage
(Courtesy of the Freyssinet Group)

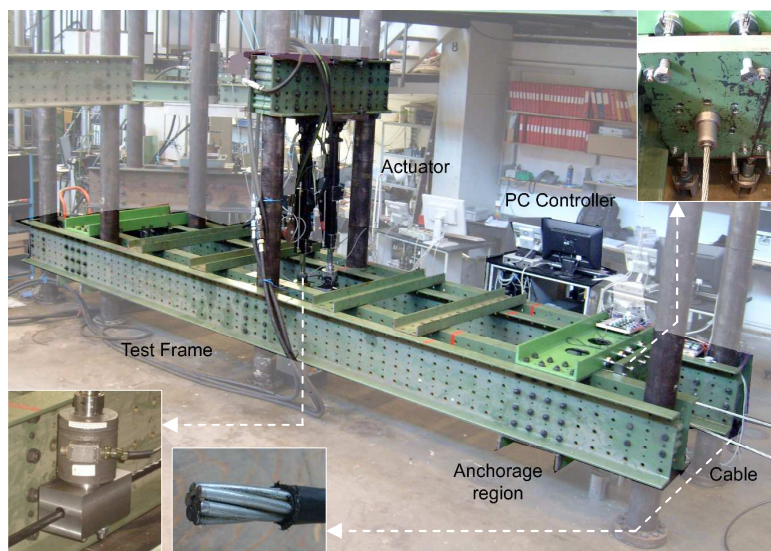
The commonly applied qualification tests for the fatigue resistance of stay cables, as outlined in *fib* [13] and PTI [14], do not specifically address fatigue issues related to transverse cable vibrations and therefore do not require testing for bending. As a consequence of this, high-strength steel cable bending fatigue spectra have not yet been developed. Thus, the calculation of the fatigue lifetime of stay cables is currently only possible for axial variations in stresses.

In this paper, the experimental investigation on the bending fatigue resistance of a high-strength steel monostrands is presented. From the fatigue tests performed, a preliminary bending fatigue spectrum curve is proposed for the conservative estimation of monostrand cable fatigue life.

2. Methodology

2.1 Specimen and Test Setup

A total of eight bending tests were carried out on high-strength monostrand steel cables with 5,1 m length and of 15,7 mm nominal diameter. The ultimate tensile strength of the cables was 1860 MPa. The specimens consisted of two layers of galvanized round wires helically spun together. The monostrands were of low relaxation grade, waxed and HDPE coated.



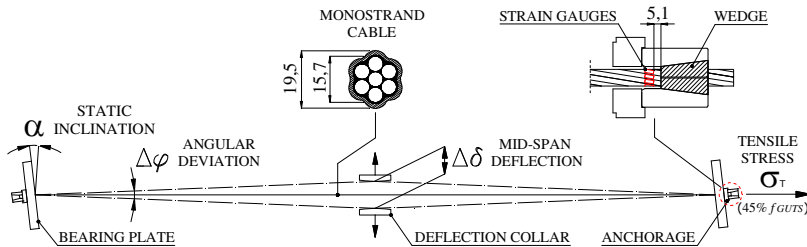
To address evaluation deficiencies and to realistically assess the fatigue lifetime of a cable, a monostrand cable test rig that can simulate flexural effects was devised, in which pre-tensioned monostrand cables could be tested under bending.

The test frame consists of four longitudinal beams and anchorage regions made of transversal profiles at both ends to resist the stressing force and the forces resulting from the bending fatigue test (Fig.2). The monostrands are terminated at both ends with the generic anchorage that prevents rotational movement.

Fig. 2: Test rig for bending fatigue tests

Each test specimen was deflected at mid-span with a deflection collar fixed to a hydraulic actuator. The deflection collar has a gradual curvature to minimize the stresses in the cable at the attachment location.

The test rig allows for both static inclination at the anchorage α (simulating installation tolerances) and dynamic variation in deflection angle of the strand. The angular deviation $\Delta\varphi$ at the anchorage was obtained by sinusoidally varying the mid-span deflection $\Delta\delta$ of the cable (Fig.3).



The monostrand cables were stressed to a tension level of 125 kN, which is equivalent to 45% of the ultimate tensile strength of the cables. The transverse deformation was provided by a hydraulic actuator attached to the deflection collar. With this test setup, bending stresses were introduced at the anchorages and the performance of the cables under bending fatigue was assessed.

Fig. 3: Simplified model of cable configuration

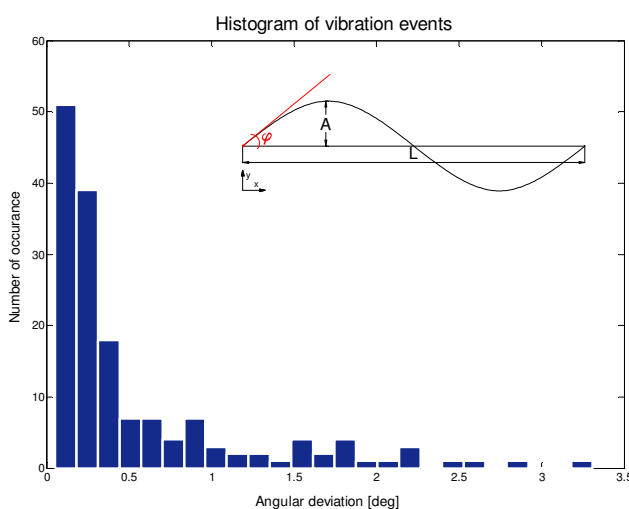
2.2 Data Acquisition System

The specimens were monitored using load transducers positioned behind the anchorage bearing plate and by load and deformation measurements at the transverse actuator. The movement of the actuator was set to be automatically stopped after initial single wire rupture. The fatigue tests were performed under displacement control at testing frequencies between 1,0 and 2,0 Hz. The stresses were measured locally at the anchorage with strain gauges attached to the individual wires of the strand. Since the maximum bending stresses in the cable occur at the anchorage, the gauges were placed close to the fixation point (Fig.3).

2.3 Angular deviation ranges for monostrand cable bending fatigue testing

Based on the information collected from the available literature and the monitoring of the Øresund Bridge [15], a database comprising of different vibration events was created. Gathered records were used to determine realistic ranges of angular deviations relevant for the bending fatigue test. The complete database can be found in [16].

Cable vibrations result in an equivalent angular deviation of the cable at the anchorage that can be determined by means of the amplitude, mode of vibration and cable length (Eq.2) assuming that the cable ends are pinned. The angular deviation is calculated as the tangent of the mode shape (Eq.1) at the ends, i.e. at the cable's anchorage:



$$\Phi(x) = A \cdot \sin\left(\frac{i\pi x}{L}\right) \quad (1)$$

$$\varphi = \Phi'(x=0) = -A \cdot \frac{i\pi}{L} \quad [\text{rad}] \quad (2)$$

where: i - mode of vibration, L - length of the cable, A - amplitude of vibration.

Fig.4 shows the histogram created from records covered in the database. The following four ranges of angular deviations were investigated in the fatigue testing: 0,5°; 1,0°; 1,5°; 2,0°. The corresponding mid-span deflections were: 22 mm, 45 mm, 67 mm and 89 mm, respectively.

Fig. 4: Histogram of cable angular deviations

3. Static Test Results

Two static tests were carried out prior to the fatigue tests to measure the stresses during the axial tensioning process at different inclinations of the bearing plate.

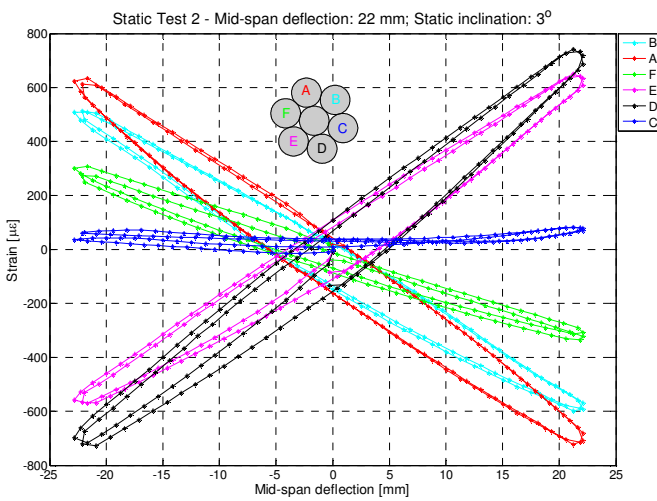


Fig. 5: Increase in wire strains at increasing mid span deflections

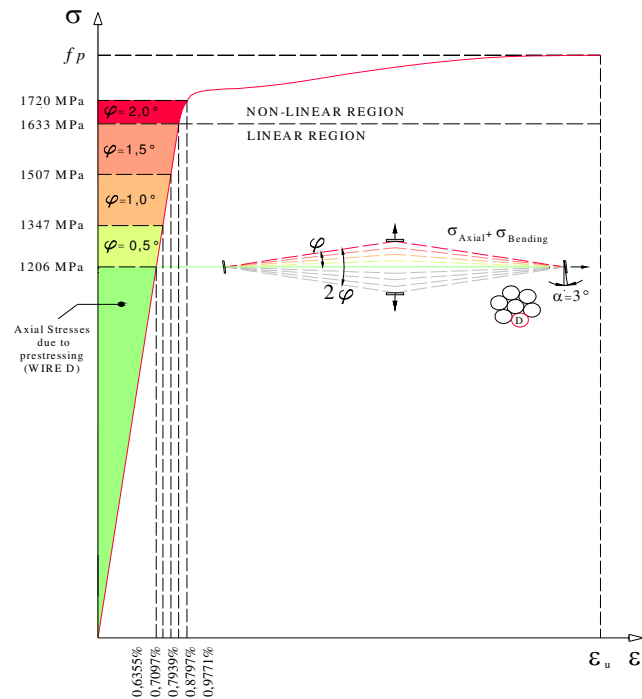


Fig. 6: Contribution to wire stresses from axial tensioning and transverse cable deflections

4. Dynamic Test Results

In all cases, the rupture of wires occurred at the location of the first tooth of the wedge (Fig.7). This was an indication that these are areas with high localized curvatures and therefore high bending stresses. The first tooth of the wedge created a flaw that initiated fatigue crack and, consequently, wire failure. Table 1 summarizes the testing parameters and the total number of cycles to single wire break. The shape of the failure surface is essentially similar in all cases and evidence of fatigue crack growth (Fig.8) suggests that rupture process was due to applied flexural load reversals.

After the axial tensioning process, each individual wire remained at a different axial strain level. The variation in stresses was caused by local bending due to the inclination of the bearing plate.

The analysis of the influence of the static inclination angle α on the wire strains can be found in [16]. It was decided to use a static inclination of 3° for the fatigue tests, as it simulates the expected installation tolerances most explicitly.

Furthermore, the variation of local strains at different mid-span deflections was investigated. Strains shown in Fig.5 represent the change in wire strain due to different mid-span deflections (axial strains are excluded).

Strain gauges on wires A and D were furthest from the centre of the cross section in the bending plane and experienced the highest total strains.

Fig.6 illustrates the contribution of bending stresses due to applied mid-span deflections to the overall stress in the strand. Increasing bending stresses correspond to an increase in angular deviation φ .

Note that when the cable strand is deflected at mid-span to 89 mm (angular deviation of 2°), wire D is reaching the yielding point. It can be seen that combined axial and bending stresses for angular deviations of $0,5^\circ$; $1,0^\circ$; $1,5^\circ$ did not exceed the linear region. However, strains due to the highest angular deviation of $2,0^\circ$ are close to the yielding point, hence the corresponding stresses were taken from the stress-strain curve provided by the cable manufacturer.



Fig. 7: Fractured strand

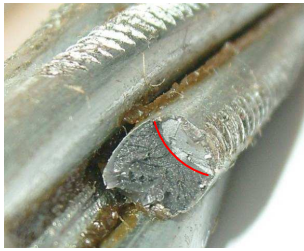


Fig. 8: Extent of fatigue crack

Table 1: Testing parameters and number of cycles to first wire breakage

Specimen	Testing parameters				1 st Wire Break
	Angular deviation φ	Mid-span deflection	Bending stress range $\Delta\sigma_{2\varphi}$	Frequency	Cycles
#1	2,0°	± 89 mm	1013 MPa	1,5 Hz	14081
#2	2,0°	± 89 mm	1013 MPa	1,5 Hz	10733
#3	2,0°	± 89 mm	1013 MPa	1,5 Hz	14948
#4	1,5°	± 67 mm	761 MPa	2,0 Hz	25177
#5	1,5°	± 67 mm	761 MPa	2,0 Hz	14350
#6	1,5°	± 67 mm	761 MPa	2,0 Hz	19872
#7	1,0°	± 45 mm	530 MPa	1,5 Hz	46855
#8	0,5°	± 22 mm	280 MPa	1,0 Hz	120047

From the bending fatigue tests reported, the following preliminary fatigue model for high-strength steel monostrand cables undergoing cyclic flexural loading has been derived:

$$\log N = 9,74 - 1,88 \cdot \log \Delta\sigma_r \quad (3)$$

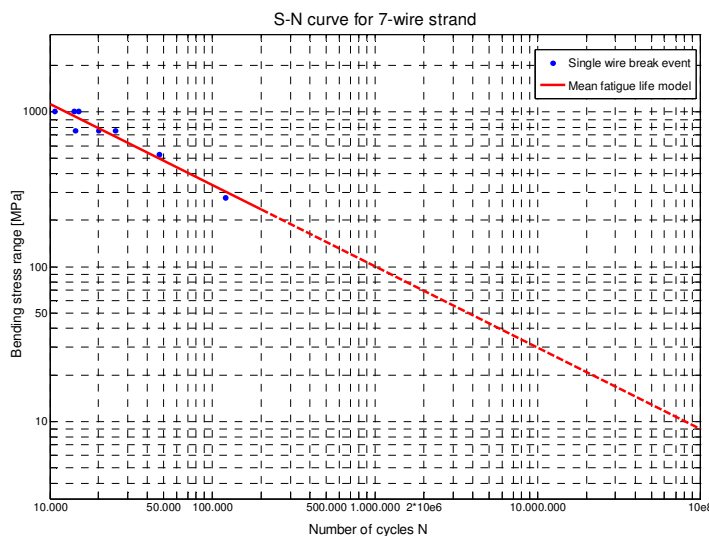


Fig. 9: Preliminary bending fatigue spectrum for monostrand

The method used to fit a predictive fatigue model to an observed bending fatigue data was the least-squares fit.

The bending stress range ($\Delta\sigma_{2\varphi}$), presented in the graph (Fig.9) refers to stresses only due to bending (peak to peak amplitude) and represent the difference between the maximum and minimum stress in the cycle.

Although no fracture of wires was observed by interwire movement that might result in fretting fatigue, it is assumed that the bending stresses are not the only parameters for assessing the fatigue lifetime of a monostrand cable.

5. Conclusions

It can be concluded that fatigue of wires was greatly influenced by local bending stresses and partially by the loading history and the mean stress. Limiting the amplitude of mid-span deflections was found to be an important factor that has the largest influence on increasing the fatigue life of the tested cable specimens. Reducing the deflection amplitude by 50% increased the number of loading cycles to fatigue failure from approximately 13 000 to approximately 47 000 in the tested specimens.

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The results show that an angular deviation of 2° can cause yielding of the high-strength steel and illustrate the relevance of bending stresses in stay cables.

From the strand tests carried out in this study, a preliminary bending fatigue model of high-strength steel monostrands has been developed. To date, there are no known code provisions or material standards addressing the bending fatigue of individual steel strands in existence. Therefore, the results presented in this paper are a step towards a better estimation of service life of these structural elements.

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