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Fatigue assessment of the collapsed XXth Century cable-stayed Polcevera Bridge in Genoa

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Abstract

The present paper investigates the combined effect of corrosion and fatigue at very-high number of cycles on the recently collapsed Polcevera Bridge. Since the construction, in the mid-sixties, the viaduct has experienced a dramatic increase in the heavy lorries traffic. Although the amplitude of stress oscillation in the strands was limited, it is assessed that the number of larger load amplitude cycles reached eighty million, out of almost half a billion of total vehicles that crossed the bridge. Due to the aggressive environment, the degradation of the bridge has developed much faster than expected. It is likely that, already at the beginning of the Eighties, the effectiveness of the prestressed concrete covering of the strands was vanishing in some sections close to the antenna, both in terms of protection and local stiffness. As a result, the levels of corrosion detected in the strands could have been sufficient to trigger the brittle failure of one of the stay cables, and the subsequent collapse of one of the self-standing structural systems. Besides to figure out the possible collapse mechanism of the Polcevera Bridge, the authors wish to rise the attention of the scientific community on the rather underestimated phenomenon of very-high cycle corrosion fatigue in existing civil infrastructures.

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Keywords: Cable-stayed Bridge ; Corrosion Fatigue ; Very-High Cycle Fatigue ; Fatigue Limit

1. Introduction

The present European standards concerning the fatigue assessment in bridges prescribe to adopt the stress life approach, and to refer to a bounded Wöhler's curve with cut-off in correspondence of 10^8 cycles (Nussbaumer et al., 2018).

Nomenclature

$p.p.$ self-weight of deck

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q dead load acting on the deck
P self-weight of Gerber beam and dead load acting on it
Q self-weight of transverse beam
V_A vertical reaction of the deck in correspondence of the stay cable
T_A axial force in the stay cable
α angle between the axes of deck and stay cable
$\sigma_{s,in}$ normal stress in the inner strands
$A_{s,in}$ reacting cross-section of the inner strands
$\bar{\sigma}_{s,in}$ mean stress of the inner strands
$\bar{\sigma}_{s,out}$ mean stress of the outer strands
$\Delta\sigma$ stress range in the stay cable
D accumulated fatigue damage
$\Delta\sigma_i$ i^{th} applied stress range
n_i number of cycles related to $\Delta\sigma_i$
N_i number of cycles to failure when $\Delta\sigma_i$ is applied until collapse

Although the existence of the fatigue limit is still controversial (Bathias & Paris, 2004), this approach looks reasonable, at least when degradation is avoided and when the load spectrum due to the heavy traffic has been correctly estimated (EN 1991-2, 2003).

The picture is different if existing bridges are considered. Especially in the case of last Century bridges, the corrosion of metallic parts can be developed more than expected due both to poor maintenance and to underestimation of the aggressiveness of the environment. At the same time, the load spectrum has dramatically increased in terms of relative and absolute frequency of the heavy lorries.

As a consequence, there is a consistent number of bridges that should be assessed with respect to very-high cycle fatigue phenomena, since they have already overcome more than 10^8 cycles, or will exceed them soon in the next decades.

The corrosion of steel elements subjected to cyclic loading in aggressive environment is known as corrosion fatigue (Pérez-Mora et al., 2015), and the resulting effects include both the reduction of the resisting cross sections and the downwards translation of the Wöhler curve together with the vanishing of the fatigue limit. When aggressive environment is combined with poor maintenance and very-high cycle fatigue, the phenomena interact together reducing the safety margin of the structure much faster than expected.

The Polcevera viaduct (Genoa, Italy), a renowned cable-stayed concrete bridge designed by Morandi (1968) some five decades ago and recently partially collapsed, is taken as case study to show that the impact of corrosion fatigue on existing historical bridges should deserve increased attention. Although forensic investigation is still under development, and without any claim to provide the ultimate interpretation for the failure, a simplified structural model is presented, which allows for the determination of the mean stress in the strands. The load spectrum is obtained based on the line of influence of the stay cable axial force traced for vertical moving loads on the bridge deck, and considering some relevant information about the lorries' statistics. The accumulation of damage is calculated according to the Miner approach, with reference to different scenarios.

It is shown that, if corrosion fatigue due to marine environment is accounted for, together with an estimated local reduction of the stay cable section of 20% circa, the accumulated damage approaches unity. Similar amount of corrosion was detected during a survey prior to the bridge collapse, but the actual danger was unfortunately underestimated.

2. Simplified structural model of the Polcevera Bridge

The Polcevera viaduct was a complex structure, which was composed by several minor spans and three main spans, besides all the connecting ramps. The collapsed part of the viaduct was linked with the adjacent parts of the bridge by means of two statically determinate Gerber beams of 36 m span each, which have been involved in the collapse (Fig. 1).

Fig. 1. Three self-standing structural systems of Polcevera Bridge.

Therefore, in order to simplify the analysis and better understand the failure mechanism, our attention has been focused exclusively on the self-standing structural system, which collapsed independently of the remaining parts of the viaduct. Furthermore, the balanced system designed by Morandi was a quite complicated structure itself and it is worth, at the first step, to limit the analysis to the bridge deck.

The deck of the self-sustained system was a multi-cell box girder 4.5 m deep and 171.9 m wide, which was supported at four points by inclined piers and two couples of stay cables (yellow and red elements in Fig. 2, respectively) hanged at the top of the A-shaped antenna. Four transverse beams, orthogonal to the girder, had the purpose to link the deck to the piers and to the stay cables.

According to Morandi's design concept (Morandi, 1967), the principal stay cables were supposed to support the permanent loads. The tension in the strands was set such as the vertical displacement of the deck at the connection point with the stay cables would vanish. As a consequence, the static scheme shown in Fig. 3 allows for an easy determination of the axial force in the two couples of stay cables due to the permanent loads, whose values are reported in Tab. 1. The tensile forces in the stay cables are obtained by projection of the vertical reaction forces in A and D on the cable direction. The statically indeterminate reactions in A and D are identical due to structural symmetry and can be derived imposing compatibility equations.

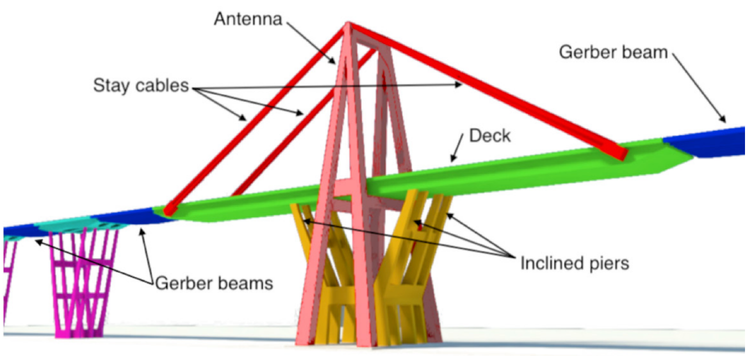

Fig. 2. Structural components of the self-sustained system.

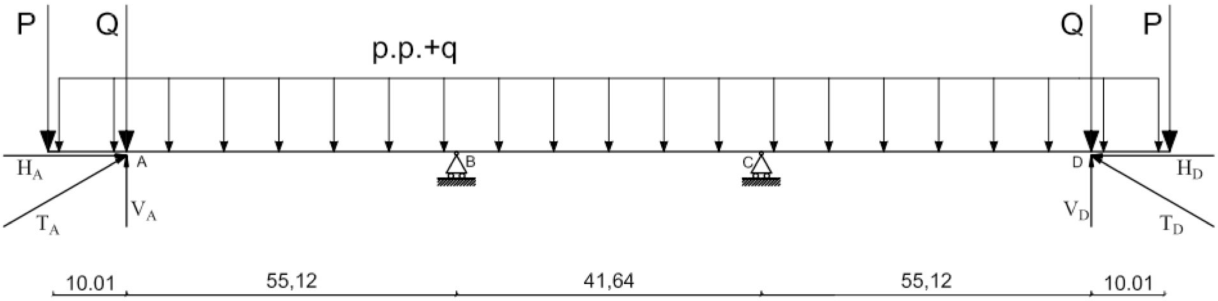

Fig. 3. Static scheme used for the evaluation of stresses in the stay cables due to the permanent loads.

Notice that the construction process was highly complex also because of the use of temporary strands, which were removed once the main stays were in place. It is worth noting that, the structural scheme represented in Fig. 3 provides the value of the axial force in the stay cables with a good approximation.

The projection of the vertical reaction force provides the axial load at the base of the stay cable as follows:

$$T_A = \frac{V_A}{2 \cdot \sin\alpha} \cong 21003 \text{ KN} \quad (1)$$

where $\alpha = 32°$ is the angle between the horizontal line and the axis of the stay cable.

Table 1. Loadings acting on the deck of the self-standing structural system.

	Type of load	Value
p.p.	Self-weight of deck	297 KN/m
q	Dead load	82 KN/m
P	Self-weight of Gerber beam and dead load acting on it	4673 KN
Q	Self-weight of transverse beam	3802 KN

In order to assess the normal stress in the strands, it is now advisable to recall some details of the construction process conceived by Morandi. At first, 352 strands with a nominal section of 93 mm^2 were connected to the deck in order to compensate the vertical displacement of the deck due to the permanent loads. During this phase, the temporary strands were gradually removed. Subsequently, the thick concrete covering was casted around the strands. This procedure was carried out casting several different segments, to avoid cracking in the concrete. In fact, due to the heavy weight of the concrete segments, the curvature of the cables changes considerably during the construction. Once that all the segments were in place, and after concrete curing, the segment joints were filled, and the concrete section pre-stressed by tensioning 112 additional strands at a final stress of 900 MPa , taking into account for the stress losses. In this way, according to the designer intention, the compressed concrete membrane would have protected the steel strands from the aggressive environment, and increased the stiffness of the stay cables. Note that, the pre-stressing of the additional strands does not change the stress of the inner tendons, since they had not yet been injected. As a result, the normal stress in the inner strands is given by the following equation:

$$\sigma_{s,in} = \frac{N_c}{A_{s,in}} \cong 642 \text{ MPa} \quad (2)$$

At the end of the construction of the stay system all the strands were injected and connected at the transverse connection beam, realizing (at least initially) a perfectly homogenized resisting cross-section.

The stress in the inner strands will be used in the next section in order to assess the fatigue load spectrum. Although this value is considered crucial for the present purposes, an even more accurate assessment of stress distribution in the stay cables components during the construction process is currently under development by the authors.

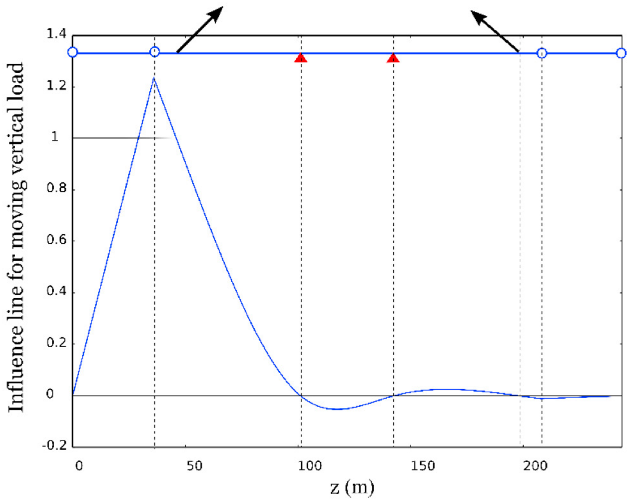

Fig. 4. Influence line of vertical reaction V_A for moving vertical load.

3. Evaluation of the fatigue load spectrum

In order to verify the stay cables with respect to corrosion fatigue, it is necessary to assess the fatigue load spectrum due to the cyclic loadings.

In general, the fatigue load spectrum can be obtained computing the stress range and the corresponding number of cycles that the structure will withstand during its service life. In particular, the European standards (EN 1991-2, 2003) provide five different fatigue load models, which require increasing levels of knowledge about the traffic statistics. Although the most precise fatigue load model would be the FLM5, as it considers the registered traffic data, in this case it is not possible to adopt it due to the lacking information about the number of lorries and the corresponding weight that has crossed the Polcevera Bridge during its service life. As a consequence, the FLM4 is used to assess the stress-amplitude time history, on the basis of a set of five equivalent lorries and disregarding the interaction between the lorries.

If we consider the couple of stay cables that support the deck at point A, in order to assess the stress range in each cable, it is necessary to calculate the influence line of the vertical reaction due to vertical moving unit load. Thanks to the reciprocity theorem, this is equivalent to trace the deflection line corresponding to the imposed unit deflection at the point A. The stress in the stay cable can be subsequently obtained by projection according to Eq. (1).

Fig. 4 shows the obtained line of influence. Taking into consideration the safety distance between lorries and according to the standard prescription, it appears that each heavy vehicle will correspond to one main load cycle (EN 1991-2, 2003). The amplitude of the cycle can be calculated multiplying the weight of the lorry by the difference between the highest peak and the lowest valley values of the influence line.

In addition, since the viaduct had one slow line for each direction, it can be considered that the heavy vehicle load spectrum in one way will be sustained by the adjacent stay cable entirely, and vice versa. The statistics of heavy lorries traffic has been estimated based on a report by Autostrade per l'Italia (Relazione Generale Sinottica, 2011), from which it emerges that the total number of heavy vehicles crossing the bridge has increased by four times since the construction. In addition, it is reported that 2, 150, 945 lorries have crossed the bridge in both directions in 2007. For the sake of simplicity, we can assume a linear increment with time of the traffic, and calculate the total number of load cycles. The weight of different typologies of lorries, and their relative frequency compared to that of the total traffic, can be deduced exploiting Tab. 4.7 of the European standard (EN 1991-2, 2003).

Table 2. Fatigue load spectrum of the stay cable.

Type of vehicle	$\bar{\sigma}_{s,in}$ [MPa]	$\bar{\sigma}_{s,out}$ [MPa]	$\Delta\sigma$ [MPa]	Number of cycles
1	649.6	1057.6	15.1	15,815,775
2	653.7	1061.7	23.4	3,953,944
3	660.5	1068.5	37.0	39,539,438
4	656.8	1064.8	29.5	11,861,831
5	659.0	1067.0	34.0	7,907,888

It is worth noting that Morandi (1979), already at the end of the Seventies, was very worried about the degradation rate of the bridge, due not only to the marine aggressive environment but also to the pollution caused by the nearby steelwork factories.

Therefore, it is reasonable to assume that, especially close to the top of the antenna, the pre-stress compression state of the concrete covering was substantially compromised. This implies that corrosion was made more severe by fatigue, but also that due to the stress redistribution, the load cycles were supported by the steel tendons alone. If even only one section of the stay cable was decompressed, the fatigue load spectrum in the tendons could be calculated as reported in Tab. 2, while the stiffness of the whole stay cable remained practically unchanged.

4. Fatigue damage accumulation

Since the stress range is not constant, a rule for the damage accumulation must be adopted EN 1993-1-9 (2005). For simplicity we assumed Palmgren-Miner's rule (Miner, 1945). Note that this assumption is not very conservative

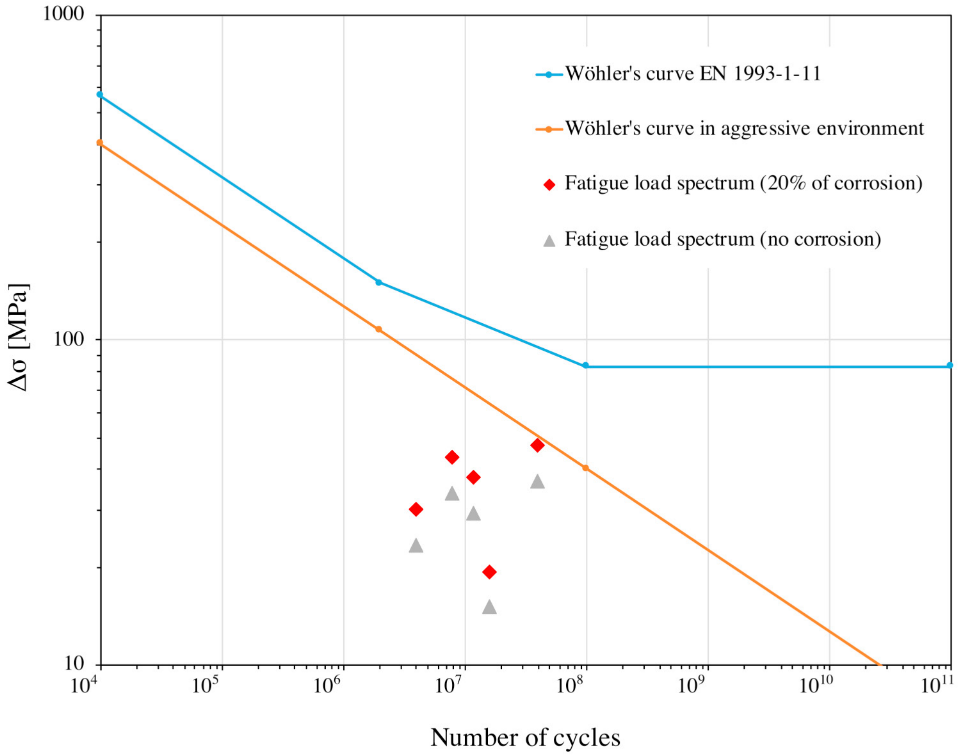

Fig. 5. Application of Palmgren-Miner's rule according to different corrosion scenarios.

and that the fatigue life could be overestimated, especially if the larger stress ranges anticipate the smaller ones (Mayer et al., 2009). Let us assume that N_i is the number of cycles to failure when the constant stress range $\Delta\sigma_i$ is applied until collapse. If $\Delta\sigma_i$ is a certain applied stress range with the absolute frequency n_i , the partial damage due to each stress range is given by the ratio n_i/N_i. The fatigue failure occurs when the accumulated damage reaches the unity:

$$D = \sum_i \frac{n_i}{N_i} = 1 \tag{3}$$

In addition, the degradation of the steel tendons must be considered from two different points of view. On one side, corrosion causes the decrement of the resisting cross-section. On the other side, Wöhler's curve itself is affected by corrosion, since the tendons surface roughness is increased by the presence of corrosion pits, and because the corrosion at the crack tip influences the fatigue crack propagation rate (Nussbaumer et al., 2018).

Different scenarios can be considered, as shown in Fig. 5. If no corrosion is considered, Wöhler's curve is provided by EN 1993-1-11 (2006) and the failure due to the damage accumulation for the given fatigue load spectrum can be excluded. If the aggressive environment is considered, Wöhler's curve changes, because the curve is translated downwards and because the horizontal asymptote is missing (Lotsberg, 2016). Analogous modification of Wöhler's curve would be obtained if the influence of structural size were additionally considered (Carpinteri & Montagnoli, 2018).

In this context, it is possible to look for the level of absolute corrosion necessary for the damage accumulation to approach unity. Since Eq.(3) can not be inverted directly, the calculation must be performed iteratively. The critical level of corrosion is estimated to be approximately equal to 20%. It is worth nothing that the level of corrosion detected during inspections, carried out in 2015, was estimated comprised between 10% and 20% (Relazione Commssione Ispettiva Mit, 2018). In addition, recent analyses carried out on the bridge's stay cable ruins (Filetto et al., 2019) provided that at least 22% of strands showed a very high level of corrosion comprised between 50% and 70%, whereas in the remaining 78% the lower level of corrosion was comprised between 30% and 50%. As a consequence, it is conservative assuming an overall level of corrosion approximately of 35%. It is worth noting that the critical level of corrosion with respect to the static load is much higher, and above 60% (Calvi et al., 2018). In addition, if the decompression of the concrete did not occur, the stress range in the tendons would have been much lower and the critical accumulated damage would have been avoided. Finally, it is evident that the concept of fatigue limit can be unsafe, and that is worthy of deeper investigations in order to better account for the influence of aggressive environment, structural size-scale, and damage accumulation in very-high cycle regime.

5. Conclusions

The recent collapse of the Morandi's Bridge has been considered and analyzed in order to verify the possible influence of fatigue to trigger the failure. It is shown that the combined effect of very-high-cycle low-amplitude fatigue and corrosion degradation can be at the origin of the collapse. In particular, the aggressive environment, as well as the structural size effect, both may change Wöhler's curve, translating it downwards and eliminating the horizontal asymptote at the basis of the concept of fatigue limit. Therefore, if the structure is subjected to a number of cycles higher than ten million, even the lowest stress range can provide relevant damage accumulation. This could have been the case of Morandi's Bridge. In addition, this could be relevant to the large assets of existing structures and infrastructures that were built during the last Century.

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