Fatigue of threaded rods in cable anchorages due to vortex shedding

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Fatigue of Threaded Rods in Cable Anchorages due to Vortex Shedding

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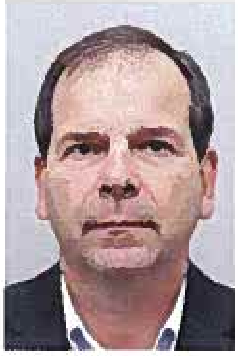

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Summary

The ‘Hovenring’ is a bicycle roundabout flyover built as a signature bridge with a central steel pylon carrying a circular bridge deck suspended through stay-cables. Shortly after installation of the bridge, the stay-cables turned out to vibrate in the wind due to vortex shedding. These vibrations have possibly caused fatigue damage in the threaded rods of the cable anchorages. Therefore, fatigue assessments were made using both traditional S-N-curves (Wöhler curves) in combination with the Palmgren-Miner damage accumulation rule as well as fracture mechanics analyses using crack growth data. The design fatigue life of the threaded rods appeared to be extremely short and therefore it was decided to replace them. This paper shows that it is a dangerous design procedure to deliberately not consider vortex shedding and possible fatigue damage in the design stage and to take measures against vortex shedding only after completion of a bridge structure.

Keywords: fatigue; stay-cables; threaded rod; cable anchorage; vortex shedding; fracture mechanics; bridge; flyover.

1. Introduction

Based on an example of a real structure, it is shown that vortex shedding of stay cables can result in an extremely short design fatigue life. The ‘Hovenring’, built in the years 2011-2012 in Eindhoven, The Netherlands, is a suspended cable-stayed bicycle roundabout flyover (Fig. 1) with a central 70 meter high steel pylon carrying a 72 meter diameter circular bridge deck through 24 stay-cables. The bridge deck is virtually floating over a motorway junction. It separates bicycles from cars, thus offering a safe passage to cyclists. It is a landmark structure and a signature bridge especially developed for this location.

End of the year 2011, shortly after installation of the bridge, it turned out that the stay-cables vibrated in the wind at moderate wind speeds. After about 23 days it was decided to stabilize the stay-cables by adding temporary cords between them. This introduced enough damping to prevent the stay-cables from vibrating in the wind. Then investigations started to determine the exact cause of the vibrations aiming at a final solution to prevent them. It turned out that vortex shedding was the cause of the vibrations and finally Salvi dampers were attached to the stay-cables.

Fig. 1: Cable-stayed bicycle roundabout flyover ‘Hovenring’ (photo courtesy of Municipality of Eindhoven)

The stay-cables are of the locked

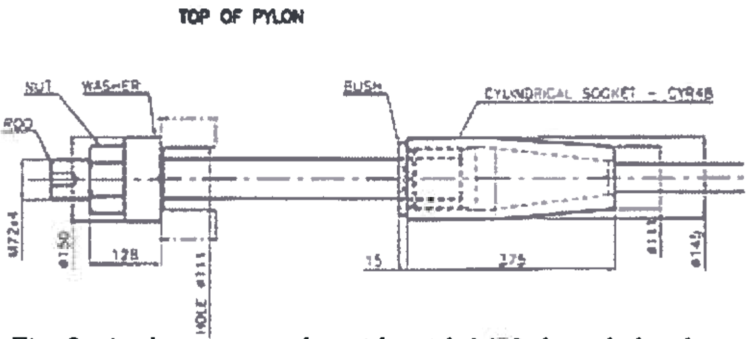

Fig. 2: Anchorage at pylon side with M72 threaded rod

coil type with a diameter of 50 mm and they have an adjustable anchorage. The cable strands are anchored in a socket which is connected to a threaded rod. The threaded rods – M72x4 at the pylon side and M100x6 at the bridge deck side – contain a nut that carry on bearing plates. The most critical part, being the threaded rod in the cable anchorages at the pylon side (Fig. 2), was assessed on susceptibility to fatigue damage.

Due to vortex shedding the threaded rods are unintentionally loaded in bending in combination with their axial loading. The bending stresses and the bending stress histograms for the 23 day period of vortex shedding of the stay-cables were determined. These were used as input for the fatigue assessment using traditional S-N-curves (Wöhler curves) in combination with the Palmgren-Miner damage accumulation rule. In addition, fatigue was assessed through fracture mechanics analyses using crack growth data. These assessment methods are extensively discussed in the full paper.

2. Results and discussion

An overview of the design fatigue lives as calculated is shown in Table 1.

Table 1: Overview of design fatigue lives (in hours) determined with discussed assessment methods

Fatigue assessment method	Preliminary fatigue assessment	Accurate fatigue assessment
	Single stress range based	Stress range histogram based
S-N-curves based – Eurocode category	0,9	0,7
– Test based category	2,9	2,4
Fracture mechanics based	5,6	4,7

The stress range based preliminary fatigue assessments yield short fatigue design lives. The longest design fatigue live is obtained using fracture mechanics because 1) the more favourable effect of bending stress can be taken into account in the fracture mechanics based fatigue assessment and 2) the size effect in the S-N-curves based code is more severe than calculated with fracture mechanics. Similar observations can be made for the stress range histogram based accurate fatigue assessment methods. All fatigue assessment methods result in far too short design fatigue lives.

3. Conclusions

On the basis of S-N-curves and fracture mechanics based fatigue assessments of the threaded rods in the stay-cable anchorages of the bicycle roundabout flyover 'Hovenring' - resulting in very short design fatigue lives - it was decided to replace the threaded rods after Salvi dampers were installed to prevent further vortex shedding of the stay-cables. The short design fatigue lives indicate that vortex shedding should be explicitly considered in the design stage. It can be a dangerous design approach to take measures against vortex shedding only after a structure is built, because severe fatigue damage may already have taken place before dampers or other devices are installed. In vortex sensitive structures, this phenomenon should be explicitly considered in the design stage.

4. Acknowledgement

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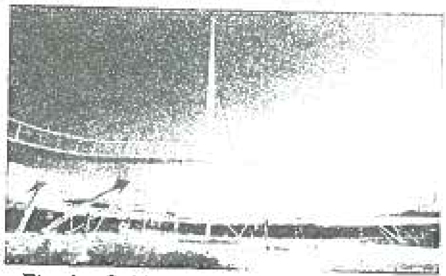

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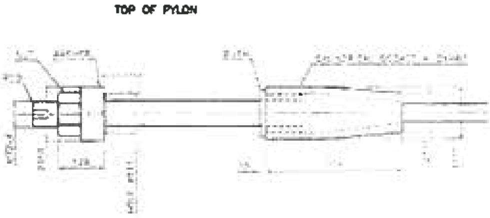
The stay-cables are of the locked coil type with a diameter of 50 mm and they have an adjustable anchorage. The cable strands are anchored in a socket which is connected to a threaded rod. The threaded rods – M72x4 at the pylon side and M100x6 at the bridge deck side – contain a nut that carry on bearing plates. The most critical part, being the threaded rod in the cable anchorages at the pylon side (Fig. 2), was assessed on susceptibility to fatigue damage.



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KOLKATA 2013

Long Span Bridges and Roofs –
Development, Design and Implementation

REPORT

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Organised by
Indian Group of IABSE

Supported by
Ministry of Road Transport and Highways, Government of India
and
Government of West Bengal

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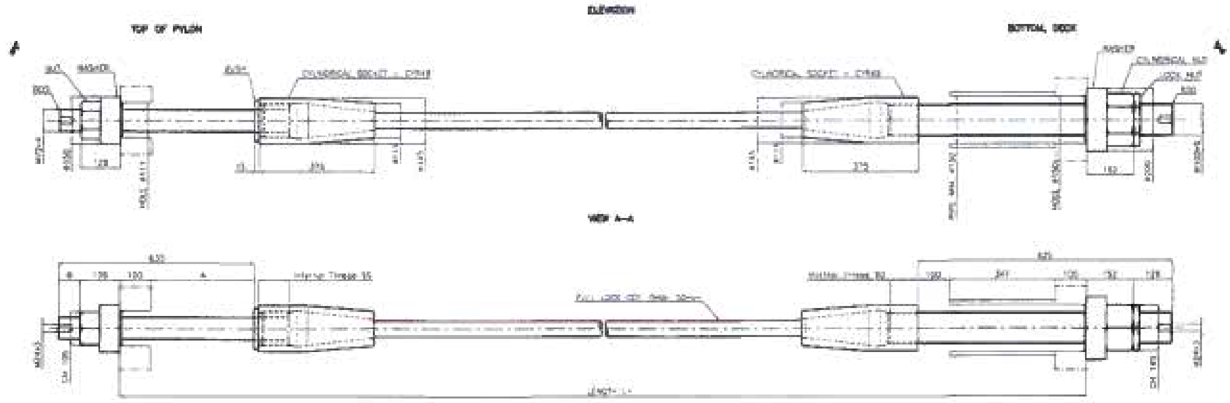
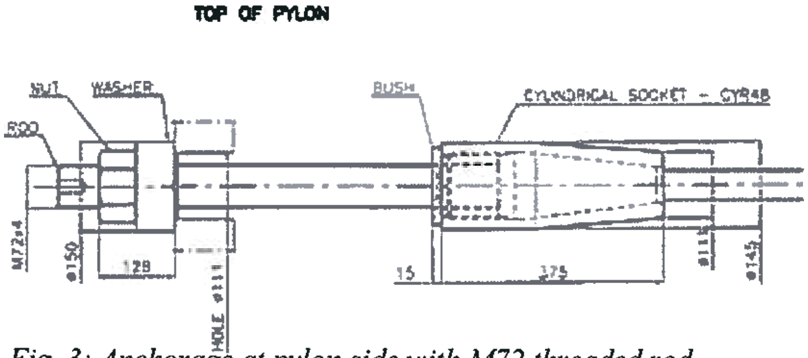


Fig. 2: Stay-cables with adjustable anchorages and sockets connected to threaded rods

coil type having a 50 mm diameter and they have an adjustable anchorage. The cable strands are anchored in a socket which is connected to a threaded rod. The threaded rods – M72x4 at the pylon side and M100x6 at the bridge deck side – contain a nut that carry on bearing plates (Fig. 2). Due to the tension force on the rod, this anchorage acts as a partial clamp. The most critical part, being the threaded rod in the cable anchorages at the pylon side (Fig. 3), was assessed on susceptibility to fatigue damage. The M72 threaded rods have a stress area $A_s = 3664$ mm^2 and they have a tensile strength $R_m = 790$ N/mm^2 and an 0,2% proof stress $R_p = 655$ N/mm^2.



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Due to vortex shedding the threaded rods are unintentionally loaded in bending in combination with their axial loading. The bending stresses and the bending stress histograms for the 23 day period of vortex shedding of the stay-cables were determined on the basis of site measurements and finite element calculations. These were used as input for the fatigue assessment using traditional S-N-curves (Wöhler curves) in combination with the Palmgren-Miner damage accumulation rule. In addition, fatigue was assessed through fracture mechanics analyses using crack growth data. These assessment methods are extensively discussed. On the basis of these fatigue assessments it was decided to replace the threaded rods since they appeared to have a very short design fatigue life. This indicates that it can be a dangerous design procedure to deliberately not consider vortex shedding in the design stage only taking measures against it once a structure is built, because severe fatigue damage may already have taken place before measures are installed. In vortex sensitive structures, this phenomenon should be explicitly considered in the design stage.

2. Preliminary fatigue assessments

Immediately after the occurrence of the vibrations, preliminary fatigue assessments were made.

2.1 Estimated stress range

The cable vibrations due to vortex shedding took place in the period from 19 December 2011, the moment right after installation of the bridge, till 11 January 2012, the moment that the vibrations were stabilised by adding temporary cords between them. Hence, the cables and their anchorages were exposed to vibrations for a period of approximately 23 days . Investigations started to determine the cause of the vibrations. It was observed that only the stay-cables vibrated in the wind at moderate wind speeds, without the deck being affected. This indicated a cable vibration problem and several phenomena were considered [1] like buffeting, vortex shedding, galloping and rain-wind induced vibrations. The latter could be excluded since the cables also vibrated in dry weather. Measurements and calculations [2] showed vortex shedding to be the cause of the vibrations. The bending stress range in the threaded rods was determined to be $\Delta\sigma_R = 122$ N/mm^2. The observed most detrimental vortex vibration frequency was indicated to be 15 Hz. So the maximum number of cycles that a stay-cable has possibly undergone is 23 days · 24 hours/day · 60 min/hour · 60 s/min · 15 Hz = $29{,}8 \cdot 10^6$ cycles. However, the wind direction and the wind speed fluctuate, so that the number of cycles one stay-cable experienced is less. Since the structure has rotation symmetry, one or more cables vibrated at moderate wind speed for all wind directions. However, with the predominant wind direction being South-West and the observation that the same cables vibrated during several days, it can be concluded that a substantial number of cycles with bending stress range $\Delta\sigma_R = 122$ N/mm^2 occurred in the threaded bars of these stay-cables.

2.2 S-N-curves based fatigue life using estimated stress range

The design fatigue life was first estimated using traditional S-N-curves (Wöhler curves) according to Eurocode 3, EN 1993-1-9 [3]. Both Eurocode and test based detail categories were considered.

2.2.1 Eurocode detail category

Eurocode 3 gives in EN 1993-1-9 [3] for 'bolts and rods with rolled or cut threads in tension' detail category 50 (Table 8.1 of [3] on page 20). Because a detail category for threaded rods in bending is not available, detail category 50 with $\Delta\sigma_C = 50$ N/mm^2 is conservatively used, where $\Delta\sigma_C$ is the reference value of the fatigue strength at 2 million cycles. The code [3] indicates that for large diameters the size effect has to be taken into account by multiplying $\Delta\sigma_C$ by a factor k_s:

$$k_s = (30/d)^{0,25} \tag{1}$$

where d is the diameter of the threaded rod. For a threaded rod M72 the diameter based on the stress area is $d = 68{,}3$ mm and thus $k_s = 0{,}81$. Clause 3 of EN 1993-1-9 [3] recommends a partial factor to be used. In the absence of a possibility to inspect and due to occurring cracks leading to sudden failure, the 'safe life' method applies. Because of the high number of stay cables, failure of one of them has limited consequences for the bridge. Therefore, 'low consequence' applies. Table 3.1 of [3] recommends for 'safe life' and 'low consequence' a partial factor $\gamma_{Mf} = 1{,}15$. The final detail category including the size effect and the partial factor is then
$\Delta\sigma_{C,d} = 0{,}81 \cdot 50/1{,}15 = 35{,}2$ N/mm^2.
The number of cycles N_R till failure can be calculated with the S-N-curve of EN 1993-1-1 [3]:

$$N_R = 2 \cdot 10^6 \left(\frac{\Delta\sigma_{c,d}}{\Delta\sigma_R} \right)^m \text{ with } m = 3 \tag{2}$$

where m is the inverse slope of the S-N-curve. With $\Delta\sigma_R = 122$ N/mm^2 and $\Delta\sigma_{C,d} = 35{,}2$ N/mm^2 in Eqn. (2), the design number of cycles to failure is calculated as $N_R = 48037$ cycles. With a vortex shedding frequency of 15 Hz the design life is 3202 s or 0,9 hours.

2.2.2 Test based detail category

The cable supplier made a fatigue test result available [4, 5]. The test was carried out in tension with a stress range of $\Delta\sigma = 105$ N/mm^2 and the M72 threaded rod resisted $2 \cdot 10^6$ cycles. The test was stopped at that moment, i.e. the number of cycles to failure was not established. In general, one single test result is insufficient for determining a design value, but the detail category can be estimated as follows. If the mean value μ would be known, then the design value is μe^{-2V} with V being the coefficient of variation. If only one single test value p is available, then the design value is $pe^{-2.8V}$. If the coefficient of variation for the fatigue life is V_n then for an S-N-curve with slope m the coefficient of variation for the stress range is:

$$V_\sigma = V_n / m \tag{3}$$

With $m = 3$ and the coefficient of variation for the fatigue life approximately $V_n = 0{,}6$ [6], the

coefficient of variation for the stress range is $V_\sigma = 0{,}2$. The estimated detail category on the basis of the test result is then $\Delta\sigma_C = 105e^{-2.8\cdot 0.2} = 60{,}0$ N/mm^2. The detail category based on the test result including the partial factor is then
$\Delta\sigma_{C,d} = 60{,}0/1{,}15 = 52{,}2$ N/mm^2.
This is about 50% more favourable than the detail category based on EN 1993-1-9 [3]. According to test results in the background document [7] to EN 1993-1-9, the size effect is less pronounced than indicated in the code itself. Neglecting the size effect would lead to a detail category according to the code of $\Delta\sigma_{C,d} = 50/1{,}15 = 43{,}5$ N/mm^2 which reasonably compares with $\Delta\sigma_{C,d} = 52{,}2$ N/mm^2 based on the test result. However, according to EN 1993-1-9 the size effect has to be taken into account.
With Eqn. (2) with $\Delta\sigma_R = 122$ N/mm^2 and $\Delta\sigma_{C,d} = 52{,}2$ N/mm^2 the design number of cycles to failure is calculated as $N_R = 156661$ cycles. With a vortex shedding frequency of 15 Hz the design life is now 10444 s or 2,9 hours. Even using the stress range applied in the test, $\Delta\sigma = 105$ N/mm^2, as average category, gives an average fatigue life of only 23,6 hours. Because the cables have vibrated for a longer period than 24 hours, this indicates that either the average fatigue strength of the threaded rod is greater than $\Delta\sigma = 105$ N/mm^2, or that assumptions made in the calculation of the stress range are somewhat conservative. These aspects are considered in the following sections.

2.3 Fracture mechanics based fatigue life using estimated stress range

The S-N curves in standards and the tests carried out on threaded rods are all carried out in tension, while the threaded rods applied in the 'Hovenring' are loaded in bending. It is known that the fatigue life of threaded rods in bending is longer than that in tension. If tests are not available, an indication of the fatigue life can be obtained with fracture mechanics.

The fatigue life of a structure consists of an initiation and a propagation stage. For bolts (and for threaded rods), especially in case of cut but also in case of rolled thread, the initiation stage is relatively small [7] and is neglected. The propagation stage can be modelled using the so-called 'simplified law' [8] based on the well-known Paris equation [9]:

$$\begin{aligned} \frac{da}{dN} &= C\cdot\Delta K^m \quad \text{for} \quad \Delta K > \Delta K_{th} \\ \frac{da}{dN} &= 0 \quad \text{for} \quad \Delta K \le \Delta K_{th} \end{aligned} \tag{4}$$

where da/dN is the crack growth rate, a is the crack length, N is the number of cycles, C is a material constant, ΔK is the stress intensity factor range, ΔK_{th} is the threshold value for ΔK below which crack extension is not to be expected, m is a constant which is the exponent in the da/dN-ΔK-curve. Eqn. (4) describes the regions I and II in Fig. 4. The stress intensity factor range ΔK is here defined as:

$$\Delta K = \gamma_{Mf} Y \Delta\sigma\sqrt{\pi a} \tag{5}$$

where Y is a geometric correction factor. Note that the stress intensity factor includes the partial factor meaning that with this model design fatigue lives are calculated. The geometric correction factor for a threaded rod in bending is based on [8] and modified to include the thread effect:

$$\begin{aligned} Y &= 2.043\exp\left\{-31.332\left(\frac{a}{2r}\right)\right\} + 0.6301 + \\ &+ 0.03488\left(\frac{a}{2r}\right) - 3.3365\left(\frac{a}{2r}\right)^2 + 13.406\left(\frac{a}{2r}\right)^3 - 6.0021\left(\frac{a}{2r}\right)^4 \end{aligned} \tag{6}$$

Where r is the threaded rod radius (Fig. 5). The first term with the exponent represents the thread effect in the same way as for a threaded rod in tension [8]. In [8], the following values for the parameters in the model are recommended: $m = 3$, $C = 5{,}21\cdot 10^{-13}$ (N, mm) and $\Delta K_{th} = 63$ N/mm$^{3/2}$. However, a different value for C was used in the calculations. The constant C was calibrated such that crack growth calculations with the fracture mechanics model lead to the same fatigue lives for M20 bolts loaded in tension as calculate using S-N-curves. For this calibration, Eqn. (6) is replaced by the geometric correction factor in [8] for tension loading. The calibration resulted in $C = 1{,}92 \cdot 10^{-12}$ (N, mm), which is a conservative value compared to the value recommended by [8].

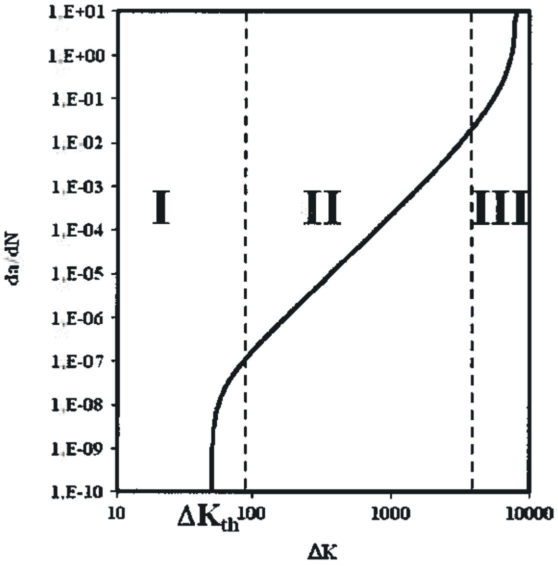

Fig. 4: Crack growth curve

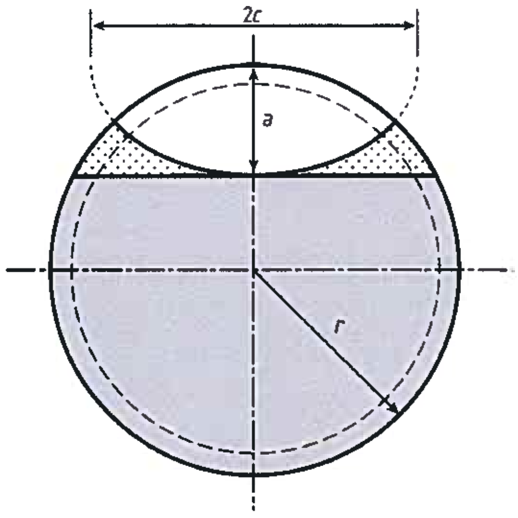

Fig. 5: Surface flaw in threaded rod

Integration of Eqn. (4) from an initial defect a_i to an end defect a_f yields the number of fatigue load cycles N_R. The maximum value of 0,15 mm and 0,004d was taken for the initial defect a_i. In case of brittle fracture, the end defect a_f is based on the material fracture toughness K_{mat} which determines region III in Fig. 4. Here $K_{mat} = 3800$ N/mm$^{3/2}$ is used but sensitivity analyses showed that the fatigue life is not influenced to a large extent by this value. Not only brittle fracture plays a role, but also plastic collapse and therefore 'assessment diagram 2' of [8] was used as failure criterion. The final crack depth turned out to be $a_f = 35$ mm for a fracture toughness of $K_{mat} = 3800$ N/mm$^{3/2}$.

With the fracture mechanics model as described, the design number of load cycles from a small assumed defect till a crack size inducing final failure of the threaded rod is determined to be about $N_R = 300000$ cycles. Based on a vortex shedding frequency of 15 Hz, this corresponds to a design fatigue life of 20000 s or 5,6 hours, i.e. approximately two times the life determined by the previous calculation based on the S-N-curve for tension loading.

3. Accurate fatigue assessments

In a later stage, more accurate fatigue assessments were made based on a more detailed assessment of the actual stress ranges that the threaded rods experienced.

3.1 Stress range histogram

Wind speed measurements from the local Eindhoven Airport were available for the 23 days vibration period of the stay-cables. Slightly lower wind speeds were measured at the bridge site having a favourable effect [9] which should however be handled with care. Nevertheless, these more favourable wind speeds were used to estimate the stress range histogram [10] shown in Table 1 (column #1 giving the stress range $\Delta\sigma_R$; column #2 giving the associated number of cycles n) to find a relatively 'optimistic' fatigue life.

3.2 S-N-curves based fatigue life using stress range histogram

The design fatigue life was first estimated using traditional S-N-curves (Wöhler curves) in combination with the Palmgren-Miner damage accumulation rule. Again, both Eurocode and test based S-N-curves were considered.

Table 1: Fatigue assessment using stress range histogram, S-N-curves and Palmgren-Miner rule

#1 $\Delta\sigma_R$ (N/mm²)	#2 n (-)	#3 N_R code (-)	#4 n/N_R code (-)	#5 N_R test (-)	#6 n/N_R test (-)
12	$1{,}11 \cdot 10^3$	∞	0	∞	0
44	$2{,}51 \cdot 10^5$	$1{,}02 \cdot 10^6$	0,25	$3{,}34 \cdot 10^6$	0,08
63	$1{,}89 \cdot 10^6$	$3{,}49 \cdot 10^5$	5,42	$1{,}14 \cdot 10^6$	1,66
83	$5{,}52 \cdot 10^6$	$1{,}53 \cdot 10^5$	36,08	$4{,}98 \cdot 10^5$	11,08
98	$7{,}45 \cdot 10^6$	$9{,}27 \cdot 10^4$	80,37	$3{,}02 \cdot 10^5$	24,67
113	$8{,}44 \cdot 10^6$	$6{,}05 \cdot 10^4$	139,50	$1{,}97 \cdot 10^5$	42,84
129	$8{,}53 \cdot 10^6$	$4{,}06 \cdot 10^4$	210,10	$1{,}33 \cdot 10^5$	64,14
129	$6{,}46 \cdot 10^6$	$4{,}06 \cdot 10^4$	159,11	$1{,}33 \cdot 10^5$	48,57
110	$4{,}62 \cdot 10^6$	$6{,}55 \cdot 10^4$	70,53	$2{,}14 \cdot 10^5$	21,59
97	$3{,}56 \cdot 10^6$ +	$9{,}55 \cdot 10^4$	37,28 +	$3{,}12 \cdot 10^5$	11,41 +
	$\sum n = 4{,}67 \cdot 10^7$		$D = \sum \frac{n}{N_R} = 739 >> 1{,}0$		$D = \sum \frac{n}{N_R} = 226 >> 1{,}0$

3.2.1 Eurocode detail category

For the stress ranges $\Delta\sigma_R$, using Eqn. (2) and the detail category $\Delta\sigma_C = 35{,}2$ N/mm² based on the Eurocode 3 EN 1993-1-9 [3], the number of cycles N_R can be calculated. However, Eqn. (2) is valid only for stress ranges greater than the constant amplitude fatigue limit $\Delta\sigma_D$ [3]:

$$\Delta\sigma_D = 0{,}737\ \Delta\sigma_C \tag{7}$$

With $\Delta\sigma_{C,d} = 35{,}2$ N/mm² the constant amplitude fatigue limit is $\Delta\sigma_{D,d} = 25{,}9$ N/mm².
The cut-off limit for variable amplitude loading is:

$$\Delta\sigma_L = 0{,}405\ \Delta\sigma_C \tag{8}$$

With $\Delta\sigma_{C,d} = 35{,}2$ N/mm² the cut-off limit is $\Delta\sigma_{L,d} = 14{,}3$ N/mm².
In EN 1993-1-9 [3], stress ranges smaller than the cut-off limit are assumed not to contribute to the damage and can be sustained infinitely:

$$N_R = \infty \tag{9}$$

For stress ranges between the constant amplitude fatigue limit $\Delta\sigma_D$ and the cut-off limit for variable amplitude loading $\Delta\sigma_L$ the following S-N-curve applies:

$$N_R = 5 \cdot 10^6 \left(\frac{\Delta\sigma_D}{\Delta\sigma_R} \right)^m \text{ with } m = 5 \tag{10}$$

For each of the stress ranges $\Delta\sigma_R$ in Table 1, the number of cycles till failure can be calculated with one of the Eqns. (2), (9) or (10) (Table 1, column #3). Subsequently the fatigue damage D can be calculated with the Palmgren-Miner damage accumulation rule [3]:

$$D = \sum \frac{n}{N_R} \qquad (11)$$

Table 1 (column #4) shows the fatigue damage calculation for the Eurocode detail category. If $D > 1,0$ the threaded rod has failed. It turns out that $D = 739 >> 1,0$ meaning that the threaded rod does not fulfill the requirements and that the fatigue life is very short. The design fatigue life can be calculated as follows:
$1/739 \cdot 23$ days $\cdot$ 24 hours/day = 0,7 hours.

3.2.2 Test based detail category

For detail category $\Delta\sigma_{C,d} = 52,2$ N/mm^2 based on the available test result, the Eqns. (7) and (8) can be used to calculate respectively the constant amplitude fatigue limit $\Delta\sigma_{D,d} = 38,5$ N/mm^2 and the cut-off limit for variable amplitude loading $\Delta\sigma_{L,d} = 21,1$ N/mm^2. Then, for each of the stress ranges $\Delta\sigma_R$ in Table 1 the number of cycles till failure can be calculated with one of the Eqns. (2), (9) or (10) (Table 1, column #5). Subsequently the damage D can be calculated with the Palmgren-Miner damage accumulation rule of Eqn. (11) (Table 1, column #6). The fatigue damage is $D = 226,04 >> 1,0$ meaning that the threaded rod still does not fulfill the requirements and that the fatigue life is very short. The design fatigue life can now be calculated as follows:
$1/226,04 \cdot 23$ days $\cdot$ 24 hours/day = 2,4 hours.

3.3 Fracture mechanics based fatigue life using stress range histogram

The design fatigue life was also determined using the stress range histogram with fracture mechanics analyses and crack growth data.

Fig. 6 shows the fatigue crack growth in the M72 threaded rod using the stress range histogram, assuming that the different stress ranges appear in random order. Sequence effects are not modelled. Fig. 6 shows that the number of load cycles from the initial defect to failure is $N_R = 400000$ cycles. Then, the fatigue damage D can be determined by dividing the number of occurring load cycles Σn (Table 1, bottom of column #2) by the number of load cycles to failure: $D = 4,67 \cdot 10^7/400000 = 117 >> 1,0$. The design fatigue life can then be calculated as follows:
$1/117 \cdot 23$ days $\cdot$ 24 hours/day = 4,7 hours.

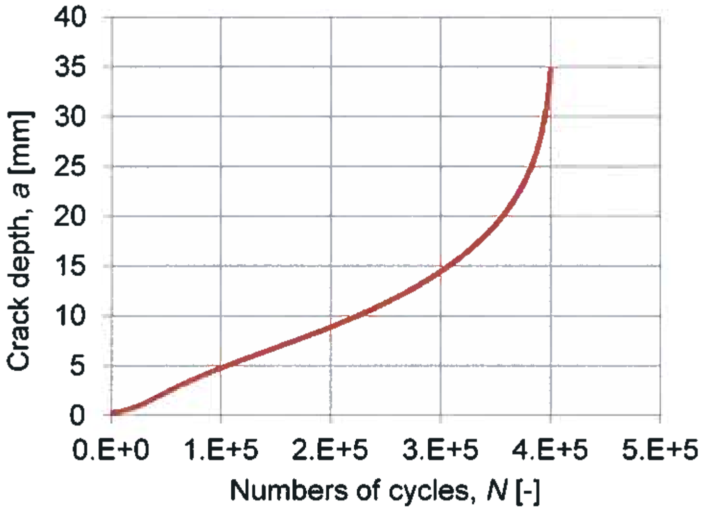

Fig. 6: Fatigue crack growth in M72 threaded rod based on stress range histogram

4. Discussion

An overview of the design fatigue lives as calculated before is shown in Table 2.

Table 2: Overview of design fatigue lives (in hours) determined with discussed assessment methods

Fatigue assessment method	Preliminary fatigue assessment	Accurate fatigue assessment
	Single stress range based	Stress range histogram based
S-N-curves based – Eurocode category	0,9	0,7
– Test based category	2,9	2,4
Fracture mechanics based	5,6	4,7

The stress range based preliminary fatigue assessments yield short fatigue design lives. The test based detail category gives a longer design fatigue life than the Eurocode detail category. An even longer design fatigue live is obtained using fracture mechanics. This is caused by the more favourable effect of bending stress which can be taken into account in the fracture mechanics based fatigue assessment while only axial stress can be taken into account in the S-N-curves based assessments. A second reason may be that the size effect in the S-N-curves based code [3] is more severe than calculated with the fracture mechanics based fatigue assessment. Similar observations can be made for the stress range histogram based accurate fatigue assessment methods. These give shorter design fatigue lives than the stress range based preliminary fatigue assessment methods. All fatigue assessment methods result in far too short design fatigue lives: the threaded rod does not meet the design life, required to take actions in preventing Vortex shedding. The threaded rods have therefore been replaced after Salvi dampers were installed to prevent further vortex shedding of the stay-cables.

5. Conclusions

On the basis of S-N-curves and fracture mechanics based fatigue assessments of the threaded rods in the stay-cable anchorages of the bicycle roundabout flyover 'Hovenring' - resulting in very short design fatigue lives - it was decided to replace the threaded rods. The short design fatigue lives indicate that vortex shedding should be explicitly considered in the design stage. It can be a dangerous design approach to deliberately not consider vortex shedding in the design stage only taking measures against vortex shedding after a structure is built, because severe fatigue damage may already have taken place before dampers or other devices are installed.

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