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FATIGUE ANALYSIS OF HANGER CABLES EXPOSED TO VIBRATIONS AT THE GREAT BELT EAST BRIDGE

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Abstract

Large amplitude hanger cable vibrations have occasionally been observed at the Great Belt East Bridge. Analysis of vibration data recorded by means of a structural monitoring system and by visual observation of the bridge have been performed in order to identify the cause of vibration and to evaluate the risk of fatigue failure in the hanger cables. Various damping systems have been installed for testing in order to identify an optimal method for reduction of the hanger cable vibrations with the object to insure infinite fatigue capacity.

A formula, called Weiss formula, for calculating angular stress for a stay cable or a hanger, has been used to convert measured relative angular rotation of the cable into an estimate of the maximum stress in the outer wires of the lock coil hanger cable at the sockets.

The lifetime assessment estimate calculated as outlined above showed in the worst case initial risk for fatigue failure from year 2015 with expected failure in year 2080. The fatigue cut-off level was calculated to correlate with hanger amplitudes of 0.5 m in the 1st mode.

Fatigue lifetime evaluations based on actual measurements on the hanger cables indicate that in the worst case, the remaining lifetime could be reduced in approximately 15 years from now, if vibrations are not controlled.

INTRODUCTION

The East Bridge, being the MAIN element in the Great Belt Link, which connects the eastern and western parts of Denmark, is a suspension bridge with a main span of 1624 m carrying road traffic on a steel box girder (fig. 1).
The locked coil hanger cables, with HDPE sheeting and an outer diameter of 80 mm to 114 mm, are arranged in pairs and interlocked by separators distributed over the length of the hanger pair at an intermediate distance of approx. 40 m.

In the early spring of 1998, during the final stages of completion, a number of large amplitude hanger cable vibration incidents were reported by workers on the bridge. These observations caused a temporary structural monitoring system to be set up in order to observe further incidents. Since then large hanger vibrations with +1 m amplitude have occurred occasionally. The large vibrations have generally been observed during the winter period on hangers with lengths of more than 100 metres.

Vibrations of hangers are difficult to control and almost impossible to eliminate completely. However it is important, that the magnitude of vibrations is minimized to such an extent that the structural integrity is maintained, and failure due to e.g. fatigue, will not occur. Sudden rupture of a hanger is a safety risk and replacements of hangers are costly and will cause disturbance to the traffic. Consequently large hanger vibrations must be avoided.

Sund & Belt, being the owner and operator of the Great Belt Link, has since 1998 made extensive efforts in finding the cause of the vibrations and subsequently developed methods to reduce such vibrations to an acceptable level by installation of different cable vibration dampers.

In order to be able to evaluate the efficiency of the cable vibration dampers and in order to determine the cause of hanger vibrations, a temporary structural monitoring system has been in operation each winter since 1998 monitoring vibrations, wind velocities, and temperatures.

Figure 1. The East Bridge

Observation History

Large hanger vibrations with amplitudes above 0.5 metres have been observed over the years. Table 1 shows an overview of observed incidences during the period from October 2000 to April 2005.

Table 1. Observations of large hanger vibration amplitudes in the years 2000 to 2005.

Date of event	Hanger ID	Max. Hanger Amplitude [m]	Wind Speed [m/s]	Wind Direction [º]	Temp [ºC]
6. March 2001	147.1N	0.9	7.2	233	2,2
16. March 2001	147.1N+S	1.3	6.8	300	2,2
29. March 2001	All	2.0	16	130	1,3
7. October 2003	149.1N	0.8	12	230	9,5
25. October 2003	149.1N	0.7	13	250	2,3
22. December 2003	146.2N - 150.1N	1.5	12	350	-2,5
20. December 2004	147.1S	0.5	11	330	1.5
21. December 2004	147.1N+S	0.5	9	230	1.5
25. December 2004	147.1S	0.8	14	170	4.0
24. January 2005	149.1S	1.8	13	20	-0.5
27. January 2005	147.1S	0.8	7	330	0.0
29. January 2005	147.1S	1.0	4	300	-0.5
2. March 2005	147.1S	1.5	12	80	-2.0
3. March 2005	147.1S	0.8	7	0	-5.0
4. March 2005	147.1S	1.3	6	180	-3.5

Vibration Mitigation Measures

Following the observation of large vibrations of March 2001, it was recognised that the hanger cable separators installed before the opening of the bridge, were insufficient to control the hanger cable vibrations and consequently further measures had to be installed in order to provide vibration control. Three different designs of cable vibration mitigation measures have over the years been tested on selected hangers, namely: Spiral Ropes, Wind Ropes, and Tuned Liquid Dampers. However none of these measures provided adequate damping as large vibrations was still measured. In November 2005, a new Hydraulic Damper system was installed on two hangers for the testing of damping efficiency.

Structural Integrity and Hanger Lifetime Assessment

In order to secure the overall integrity of bridge structure, it is important to also follow and evaluate the remaining fatigue lifetime of vibrating hangers. Based on observations and data from the vibration monitoring programme collected in the years from 2000 until 2005, an assessment of remaining lifetime of the hangers in respect of fatigue has been made. This lifetime assessment estimates in the worst case a risk of initial fatigue as from year 2015 with expected failure in year 2080. However, only a few hangers are estimated to be critical for such fatigue failure during the 100 years design life of the bridge.

As mentioned, a continuous effort to develop measures to reduce the vibrations to a level where infinite fatigue capacity of the hangers can be expected is being made, and in this context, a better knowledge of the actual fatigue capacity due to bending of locked coil cables is being searched for.

MONITORING OF VIBRATIONS

The monitoring system to identify vibrations is based on accelerometers and tiltmeters installed at –

- the second hanger pair relative to the west pylon,
- in the girder,
- at the main cable above the instrumented hangers,
- and in the pylon top.

Furthermore GPS has been placed at the pylon top and above the instrumented hangers in the main span. In addition tiltmeters have been installed on the hanger pair south-west to the pylon. See Figure 2 and 3.

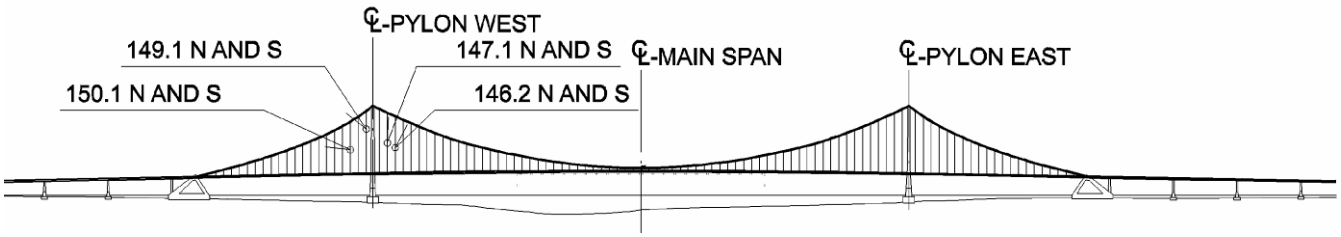

Figure 2. East Bridge - Hangers with monitoring system indicated.

Analysis of Large Amplitude Events

During October and December 2003 new large amplitude hanger vibrations were observed and monitored, followed by several incidents in the winter of 2004/2005.

These incidents were all well documented through the monitoring system and provided basis for carrying out analysis of the cable vibration excitation mechanism.

All available vibration records obtained by the monitoring system from 2001 - 2005 were post processed and analysed. The objective of this processing was to single out physical vibration events from noise, to convert acceleration amplitudes (m/s2) to displacement amplitudes (m), and finally to assess accumulated fatigue damage of the cable at the sockets of the hangers by establishing a transfer function from measured acceleration to measured angular bending at the top socket. In order to be able to carry out fatigue stress analysis for all hangers instrumented by accelerometers and not only the two hanger pairs 147.2 and 147.1 as shown below.

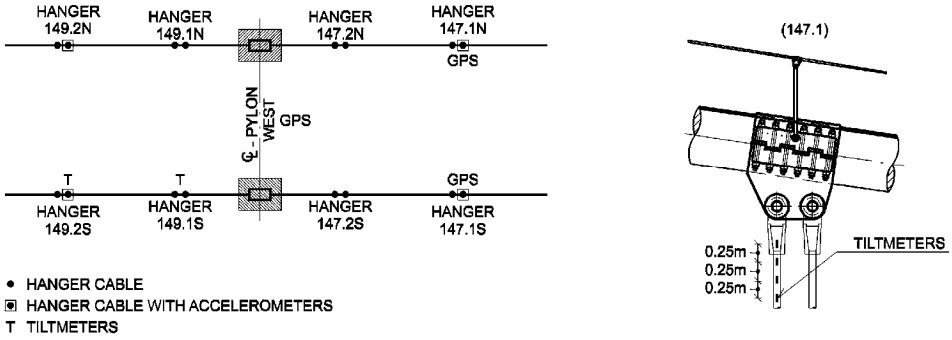

Figure 3. Layout of the monitoring system for accelerometers, tiltmeters and GPS.

This post processing was carried out - by band pass filtering of all acceleration signals in the frequency range 0.3 Hz - 4.0 Hz, - by calculation of displacements by double integration of the acceleration signals using a low pass frequency of 0.3 Hz, and finally by conversion of displacement signals from accelerometer position to middle position of the cable.

A total of 15 large amplitude events were detected which displayed amplitudes larger than approximately L/500. The corresponding date, hanger no., duration (min.), and amplitude ranges (m) were listed.

For the tiltmeters installed at the hanger pair 149.2 South the angle data were post processed by band pass filtering from 0.3 - 4.0 Hz followed by calculation of the relative angular rotation kink between the tiltmeter on the top socket and the tiltmeters on the cable expressed by applying a RMS fast filter to the signal.

Correlation with Meteorological Data
Analysing the location of incidents of large hanger vibrations has not shown any correlation between location on the bridge and the wind direction. In addition the correlation to wind speed is low.

It can be derived from meteorological data that the turbulence is low, e.g. laminar winds are dominating at large hanger vibrations. Also, a high correlation to temperatures between -5°C - 2°C can be seen together with high humidity. This is in good agreement with the fact that observations have always been made at winter time. Furthermore visual observations have often shown ice building up in droplets on the hanger cables vibrating with large amplitudes.

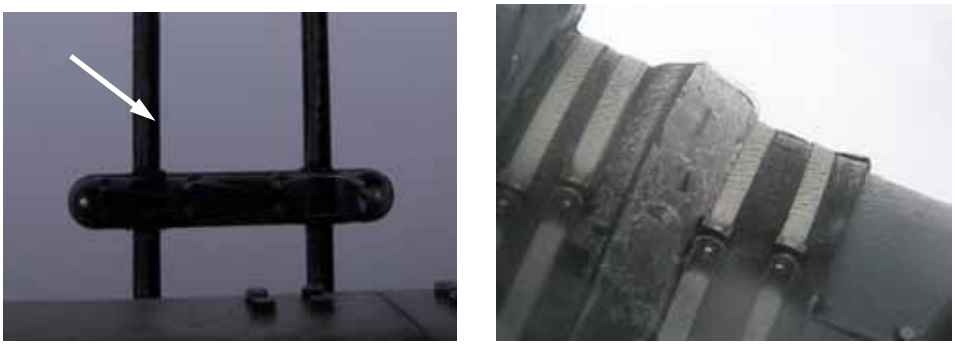

Figure 4. Ice forming on main cables and hangers (glazing)

Vibration Excitation Mechanism
Vibration excitation mechanisms have been considered as follows: - Parametric excitation, - Vortex shedding, - Wake galloping and - Ice induced galloping.

Although no evidence for any particular excitation mechanism has yet been found, indications point towards ice/wind induced galloping. Preliminary analysis of correlation between hanger cable vibrations and the small vibrations of the main cables, the pylons and the girder, has given no proof for parametric excitation. Neither does the scattered pattern in hanger cable length subjected to wind point in the direction of parametric excitation or vortex shedding. Wake galloping can be the excitation mechanism in some of the incidents as hangers near to the pylons often are subjected to large vibration incidents. However, the fact that incidents have only been observed at temperatures near 0° C and that ice glazing have been observed during at least two incidents, points towards ice/wind induced galloping.

VIBRATION LIMITATION REQUIREMENTS

The requirement for allowable maximum amplitudes of hanger vibrations has been derived based on visual comfort and fatigue assessments.

Visual Comfort
Hanger vibrations must not have the visual effect of giving safety concerns to the users of the bridge. A consequence could be lack of concentration leading to accidents or stop of the traffic. It has been assessed that amplitudes less than 1/500 of the cable length or less than 2 x the cable diameter are difficult to observe and should as such not cause visual discomfort.

Fatigue
A formula, see [2], $\sigma_{f,\max} = 2\alpha\sqrt{E\sigma_t}$, for calculating angular stress for a stay cable or a hanger, has been used to convert measured relative angular rotation of the cable into an estimate of the maximum stress in the outer wires of

the lock coil hanger cable at the top socket. The top socket is the most fatigue exposed part of the hanger as no deviator or damper is installed here.

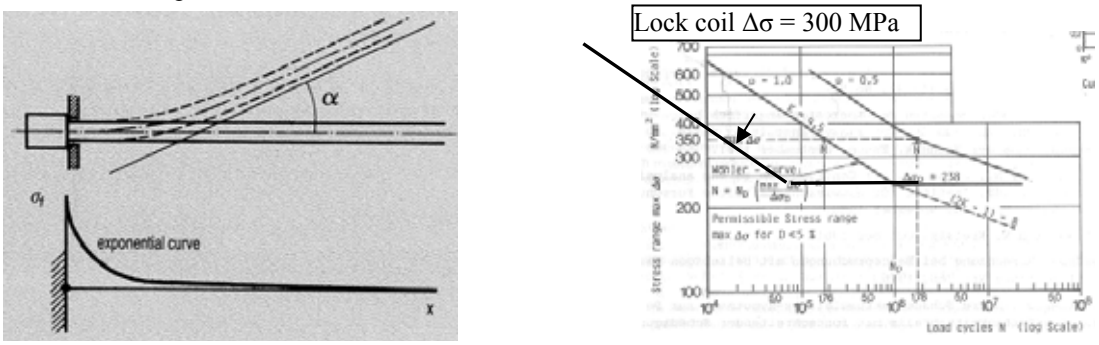

Figure 5. Bending form at top socket and SN curve used for fatigue calculations..

The fatigue calculations from the estimated maximum angular stress are based on calculating Miners No according to ASTM E-1049 -Standard Practices for Cycle Counting in Fatigue Analysis.

The characteristic SN curve applied, figure 5, has been derived from fatigue tests carried out by the cable supplier Radelli on cable wires for $\Delta\sigma = 300$ MPa at 2×10^6 load cycles. A best estimate for the slope of the SN curve, m = 4.5, and a cut-off value of 238 MPa has been used based on experience from parallel wire stay cables [1]. A similar SN curve at $\Delta\sigma = 300$ MPa at 10^6 load cycles has been used as a conservative estimate for the fatigue capacity.

The fatigue calculations were carried out on the maximum amplitude incidents recorded in the winter 2005. To estimate the fatigue capacity it has been assumed that the hangers are exposed to 10 incidents per year, similar to the hanger for which measurements are available.

Table 2 shows the Miners no. calculated for all instrumented hangers at the west pylon as the developed fatigue damage at one vibration incident of 3 hours with amplitudes of minimum 1.5 m and the remaining lifetime if 10 such incidents occur every year.

The table also shows as expected, that the damage is largest in the transversal direction towards the girder as there is no bearing the socket can rotate along in this direction, and at the same time the hanger will be exposed to the main cables low mode transverse vibrations.

It can furthermore be seen from table 2 that hanger 149.2 has obtained the most damage with a resulting rest lifetime of 15 years. The second hanger relative to the pylons is carrying the double dead load introducing a negative bending moment for the girder passing free hanging through the pylon.

Table 2. Result of rain flow counting on data using m=4,5 and $\Delta\sigma$ =238 MPa at $2x10^6$ stress cycles.

Hanger ID Amplitude L: Longitudinal T: Transversal	Characteristically fatigue for 1 incident of 3 hours with min. amplitude 1.5 m		Remaining lifetime in years at 10 incidents of 3 hours pr. year
	Miners no	Damage [%]	
149.1S 0,25 m L	8,38E-05	0,0%	1193
149.1S 0,25 m T	3,02E-04	0,0%	331
149.1S 0,50m L	1,60E-04	0,0%	625
149.1S 0,50 m T	3,72E-04	0,0%	269
149.2S 0,25 m L	6,55E-05	0,0%	1527
149.2S 0,25 m T	3,16E-03	0,3%	32
149.2S 0,50m L	2,25E-03	0,2%	44
149.2S 0,50 m T	6,85E-03	0,7%	15

It has also tried to use a more conservative SN curve by taking into account that the cable is a lock coil cable and not a parallel wire cable. The results can be seen in table 3.

Table 3. Result of rain flow counting on data using m=4,5 and $\Delta\sigma$ =238 MPa at 10^6 stress cycles.

Hanger ID Amplitude L: Longitudinal T: Transversal	Characteristically fatigue for 1 incident of 3 hours with min. amplitude 1.5 m		Remaining lifetime in years at 10 incidents of 3 hours pr. year
	Miners no	Damage [%]	
149.1S 0,25 m L	1,49E-05	0,0%	6711
149.1S 0,25 m T	5,37E-05	0,0%	1862
149.1S 0,50m L	2,84E-05	0,0%	3521
149.1S 0,50 m T	6,62E-05	0,0%	1511
149.2S 0,25 m L	1,16E-05	0,0%	8621
149.2S 0,25 m T	5,61E-04	0,1%	178
149.2S 0,50m L	4,00E-04	0,0%	250
149.2S 0,50 m T	1,22E-03	0,1%	82

The lifetime assessment estimate calculated as outlined above shows the worst case initial risk for fatigue failure from year 2015 with expected failure in year 2080. However, only the hangers in the 2nd position relative to a pylon are estimated to be critical for fatigue failure during the 100 years design life of the bridge. The cut-off level can be

calculated to correlate with hanger amplitudes of 0.5 m in the 1st mode giving the fatigue requirement to damping measures for cable vibrations.

VIBRATION MITIGATION

Damping systems
The following types of measures for mitigation of cable vibrations have been installed for testing as supplement to the cable separators:

- Spiral Ropes (installed 2001)
- Wind Ropes (installed 2001-2002)
- Tuned Liquid Dampers (installed 2004)
- Hydraulic Dampers (installed 2005)

The choice of damping system was based on evaluation of effectiveness, experience, aesthetics, installation maintenance costs, and complexity.

The list of cable dampers tested on the East Bridge clearly reflects that the dampers, with time, get more and more complex with increasing installation and maintenance costs.

As an alternative to the hydraulic dampers it has been considered to install semi active dampers of the MR type (Magnetorheological fluid dampers) which need power input. MR dampers suitable for cable damping are commercially available although expensive and have been used in new major cable supported bridge structures.

Another alternative damping method could be installation of active dampers. However, this system is more complicated and sensitive for operation and maintenance, and no experiences from other suspension bridges are yet available to justify such installation.

Hydraulic Damper
Hydraulic Damper systems have been installed at two hanger locations (See Figure 6). The fixation point of the damper is 3.6 metres above the lower anchorage and the damper is expected to increase the total damping of the hanger to the required level of 0.6% (rel. to critical).

The damping effect is provided by two cross mounted hydraulic cylinders with individual damping coefficients of 90 kNs/m or 120 kNs/m (see Figure 7). Due to the cross mounting of the hydraulic cylinders, the effective damping coefficient will depend on the direction of the hanger vibration.

Figure 6. Hydraulic Damper position

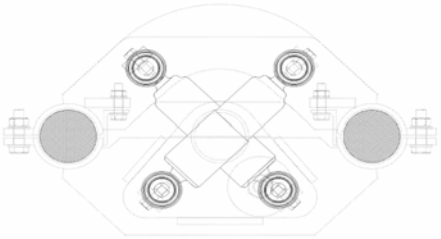

Figure 7. Hydraulic Damper Cylinder relative to hangers.

CONCLUSIONS

It has not yet been possible to identify a damping system which can reduce the large amplitude hanger cable vibrations to an acceptable level. The process with tests of damping systems and monitoring of the hanger cables vibrations will therefore continue, in order to finally identify the course of the vibrations and develop an effective damping system.

Fatigue lifetime evaluations based on actual measurements on the hanger cables indicate that in the worst case, the remaining lifetime could be reduced in approximately 15 years from now if vibrations are not controlled. Installation of an effective system to reduce the large hanger vibrations to an acceptable level is therefore imminent and must be found within the near future.

The damping effect from the Hydraulic Dampers now installed on 2 hangers is not yet available but will hopefully be obtained during the winter period 2005 - 2006. The costs of the Hydraulic Dampers are relatively high compared to the other cable vibration mitigation systems, however experience from systems installed at similar structures have proven good efficiency.

The number of hangers to be damped could be up to 80, consequently it is important to establish a reliable decision basis with conclusion on all the relevant parameters discussed.

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2. C. A. Prato; Dynamic Bending Stresses near the Ends of Parallel Bundle Stay Cables; Structural Engineering International, pp 64, 1/2003