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NOISE CONTROL FOR A BETTER ENVIRONMENT

Noise mitigation of Old Årsta railway steel bridge

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ABSTRACT

With its central role in Stockholm's railway infrastructure, the Old Årsta bridge is busy around the clock. This 1929 steel bridge is owned and operated by the Swedish Transport Administration (Trafikverket) and recently underwent renovation work. Subsequently, a need for noise mitigation was identified. However, the infrastructural role made it a prerequisite that traffic could not be affected neither during investigation nor installation of mitigation means. A comprehensive pre-study of the noise issue was previously published at Internoise 2017. It led to the installation of a multi-component CLD solution (Constrained Layer Damping). This paper presents findings from measurements of noise and structural properties after the CLD installation. A satisfactory noise reduction was obtained, and various learning points are presented. The applied mitigation strategy, using different layers of temperature dependent viscoelastic polymers, appeared to be both efficient and practical.

Keywords: Railway, Damping, Noise control
I-INCE Classification of Subject Number: 38

1. INTRODUCTION

The Old Årsta bridge in Stockholm (Sweden) was constructed in 1920 to 1929, and continues to play a central role in one of the main railway lines. It is a double track steel bridge with a main span of 151 m. Recent refurbishment of the bridge, including deck retrofitting, led to reports of increased noise from train passages. On that basis, the Swedish Transport Administration initiated a project with focus on noise reduction. Due to continuous traffic, any related measurement work and installation work had to be done in a non-intrusive manner, without access to the top of the bridge deck. On this background, Vibratec and the consulting branch of Lloyd's Register (LR) carried out a comprehensive pre-study (1).

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After careful consideration of the pre-study findings, the Swedish Transport Administration together with Vibratec and LR decided to implement the recommended add-on mitigation solution. The latter was the multi-patch Constrained Layer Damping (CLD), which was found to be the best with regard to performance, practicality and budget. This differs from past mitigation approaches involving modifications of the track (2, 3). However, the CLD solution could be installed without affecting the traffic and without access to the top side of the deck. Thompson (2) lists several examples of targeting the bridge steel structure directly, with varying results in terms of noise reduction. In the discussion, it is mentioned that the achieved reduction was limited in general by the amount of damping already present in the untreated structure. Furthermore, the balance between rolling noise and noise radiated by the bridge structure plays a limiting role.

In certain cases, structural damping may be added using vibration absorbers (4). This solution is, however, quoted as being suitable only for frequencies below 150 Hz.

In a previous industrial context, LR and Vibratec successfully designed and applied a CLD solution to a vibration problem (5). This design was further developed for the Old Årsta bridge case. Based on laboratory climate chamber testing, an appropriate CLD configuration was found. Vibratec provided and installed the solution on the Old Årsta bridge. After concluded installation, measurements of noise, vibration, and structural damping were taken by LR. The obtained results as well as other findings are described in this paper.

Vibratec's commercially aimed video (6) is recommended for a good overview of the study.

2. SUMMARY OF PRE-STUDY

The pre-study described previously in (1) involved both *in-situ* measurements and numerical modelling. Measurements included train passage noise registered at the New Årsta bridge (Pos A), located approximately 45 m to the west of Old Årsta bridge, see Figure 1.

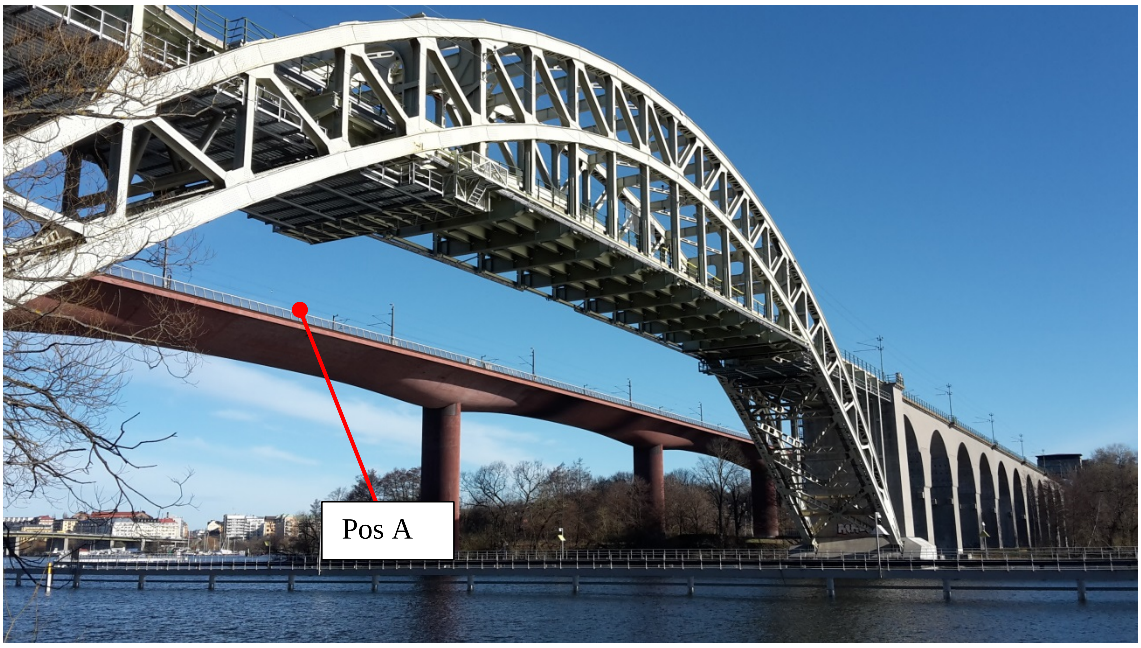

Figure 1. View from South East. In front, Old Årsta bridge. In the back, New Årsta bridge. Photo from April 2017.

Also from the Old Årsta bridge, passages were captured using LR's in-house, 56 microphone array. Furthermore, vibration measurements on multiple components of the Old Årsta bridge were taken for each vehicle passage. For both noise and vibration, precise timing of vehicle passage was determined using accelerometers mounted to the underside of the deck at each end of the Old Årsta bridge.

During times with no vehicles on the bridge, point mobility was measured for several bridge components.

Based on the empirical findings, numerical models were constructed to describe the radiated noise. In the commercial Statistical Energy Analysis (SEA) software VAOne a simplified representation of the bridge structure without hangers and arches was constructed, assuming excitation by a line of vertical, uncorrelated point sources along the centre line of one railway track. The force sources were assigned with white noise with unit amplitude, and the bridge components had structural damping corresponding as measured on the unmitigated bridge. The model results were used for ranking the noise contributions of individual bridge components to a virtual receiver at 45 m to the side, corresponding to the real-world measurement position Pos A on the New Årsta bridge. Subsequently, structural damping in the SEA model was updated corresponding to lab testing of numerous CLD solutions in a climatic chamber, leading to a prediction of the corresponding noise insertion loss.

In addition, a simple, combined prediction model for the noise at Pos A was established, which in absolute numbers predicted the partial contribution from the main bridge components (deck, longitudinal girders, flanges of longitudinal girders, etc.). To this end, the model combined measured vibration spectra with sound radiation indices.

Passage of the steel bridge was typically around 6 s, with average overall $L_{Aeq,T}$ (A-weighted, equivalent continuous sound pressure level, for time interval T) 83 dB(A). The 1/3-octave noise spectrum was dominated by the 500-800 Hz range, see Figure 2.

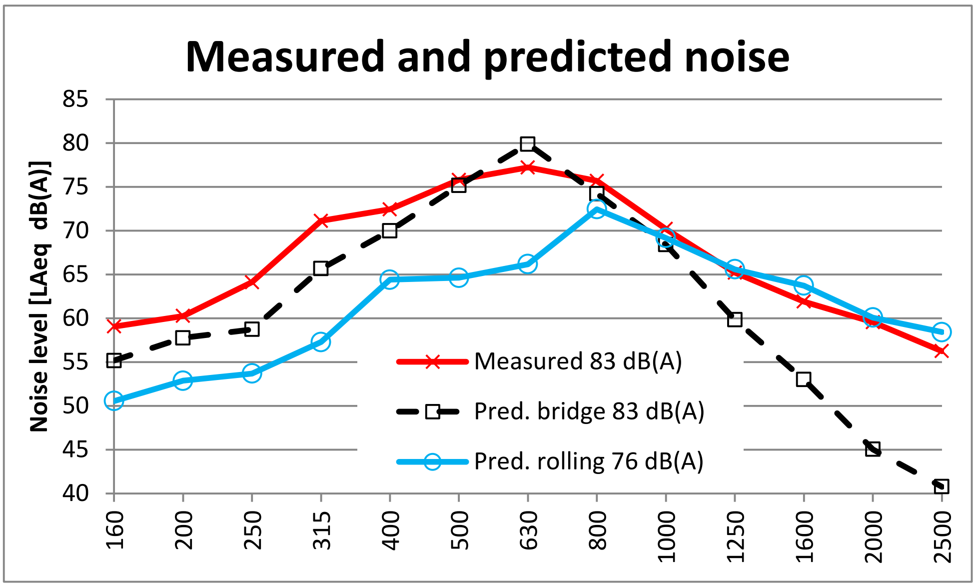

Figure 2. 1/3-octave noise spectra at Pos A for unmitigated bridge, predicted and measured

MDOF curve fitting of impact based point mobility measurements provided structural damping ratio estimates of the bridge components before mitigation. These were typically 0.5-1% of critical damping, and lowest flexural natural frequencies were found in the 50-100 Hz range.

Using the numerical models it was found that frequency range up to 800 Hz was dominated by noise radiated by the bridge structure, "bridge noise", see Figure 2.

Above 800 Hz, the “train”, or rolling, noise took over and dominated. The deck and longitudinal girders were identified as the most significant contributors to the noise at Pos A.

A maximum obtainable noise reduction at Pos A of approximately 6 dB was found, in the hypothetical case of ideal damping of the bridge structure without mitigating the vehicle part of the noise.

When considering the combined noise from the bridge structure as well as vehicle noise, this potential was found to be maximum 4 dB using CLD techniques.

3. DESCRIPTION OF THE INSTALLED CLD SOLUTION

3.1 Decided CLD solution

Following the pre-study of (1), more detailed considerations were taken as to which CLD solution to be installed, as well as installation details.

In particular, the temperature dependence of the numerous (>10) CLD solutions from the lab testing was an issue. It was decided to seek a solution with consistent noise reduction performance regardless of summer or winter climate. This was a compromise, as “optimum” CLD solutions had indeed been found that might reduce the noise even a few dB more, but only in either the summer or winter scenario.

The Swedish Transport Administration decided to install the CLD type described as follows:

The applied CLD system consists of a single layer concept using two different polymers with glue optimized for -10 ° C and + 20 ° C.

Each type of material of a CLD is normally considered as a single layer. However, note that the current design is in fact a 3-layer system, since glue as well as bitumen layer have viscoelastic behavior. System and method were previously described in (1). Constraining steel sheets were of thickness 4 or 5 mm depending on specific CLD patch, and deck/girder thickness.

Figure 3. Mounting of CLD element onto transverse plate.

3.2 Size considerations for CLD elements

Other topics that were addressed were surface coverage scenarios, and CLD element sizes. Due to the complex construction details of the bridge (see e.g. photo in Figure 4), it was unrealistic to assume perfect coverage of all steel plates. Vibratec conducted a detailed geometric survey of the as-built bridge structure. It was found that approximately 80% of the plating could in practise be treated with CLD elements.

Figure 4. Point mobility measurement of transversal plate with installed CLD solution.

The established numerical models from the pre-study were used to find a CLD element distribution according to the available plating surface, which would lead to the optimum noise reduction.

Ideally, the individual CLD elements would be tailor made to each and every intended position. Considering the size of the bridge and the complexity of the bridge design, this was however not realistic. Furthermore, the CLD elements were to be handled and installed manually from below the deck, putting significant restrictions on size and weight of the element. A good impression of the installation is obtained from the YouTube video (6). On one hand, the CLD elements must be small enough for practical handling, while at the same time being sufficiently large to provide structural damping.

As a rough guideline for CLD element sizing, the structural wavelengths were assessed for the bridge plates. Noise is mostly radiated by flexural waves, and as a rule-of-thumb, at least 80% of a wavelength must be covered by the CLD in order to obtain significant damping. Plate thickness of the bridge components was 18 mm and 30 mm for girders and deck. Bottom flanges of longitudinal girders was 50 mm. Considering idealised steel plates, Table 1 shows the relation between frequency, flexural wave speed C_B, and wavelength λ for the predominant thickness cases.

	t=18 mm		t=30 mm		t=50 mm	
Frequency [Hz]	**C_B [m/s]**	**λ [m]**	**C_B [m/s]**	**λ [m]**	**C_B [m/s]**	**λ [m]**
100	133	1.3	171	1.7	221	2.2
200	188	0.9	242	1.2	313	1.6
300	230	0.8	297	1.0	383	1.3
400	265	0.7	343	0.9	442	1.1
500	297	0.6	383	0.8	494	1.0
600	325	0.5	420	0.7	542	0.9

Table 1. Estimated wavelengths for predominant thicknesses t of bridge plates.C_B is bending wave speed, λ is wavelength of the bending wave.

A maximum, basic CLD element size of 1.0 m x1.0 m was deemed practical for manual handling. From Table 1 it follows that target wavelengths of 1.0 m / 80% = 1.25 m would correspond to frequencies of approximately 100 Hz to 400 Hz for the considered base plate thicknesses. In other words, the 1 m by 1 m CLD element would be expected to provide damping for frequencies above this approximate range. Since the pre-study indicated that the noise was dominated by the frequency range approximately 500-800 Hz (see Figure 2), the 1 m by 1 m CLD element size was selected as the design basis, with allowance for practical adjustments where needed.

In further support for the selected element size, it is noted that the pre-study indicated that the lowest flexural modes (or natural frequencies) occurred in the 50-100 Hz range for the unmitigated plates. Hence, the target frequency range was significantly higher, implying a reasonable modal density. Vibratec created a 3D structural Finite Element model of a section of the bridge, using commercial software MIDAS NFX. A numerical modal analysis was performed for 200-900 Hz, and as expected a high modal density was found. Plots of modal patterns like the examples in Figure 5 were used to confirm that wavelengths for the 100-400 Hz range were indeed less than 1.25 m, as indicated by the coarse calculations of Table 1.

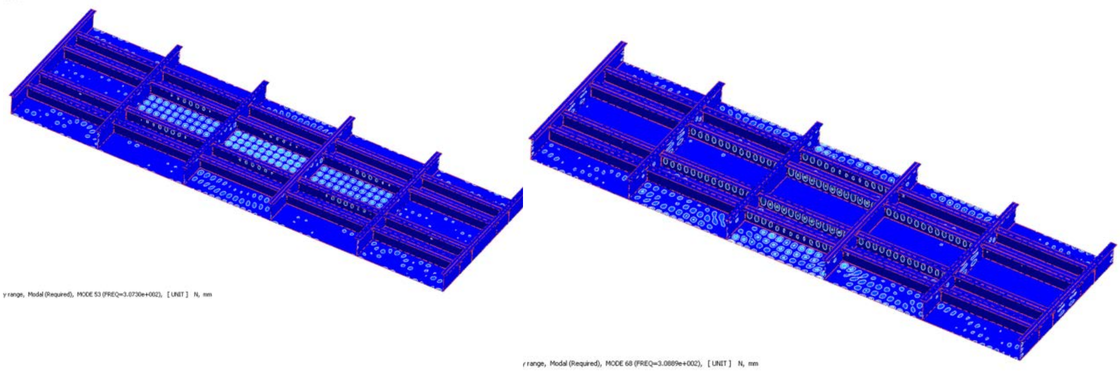

Figure 5. Examples of local modal patterns calculated using Finite Element. Left is 307.3 Hz. Right is 308.9 Hz. Bridge deck with girders is seen from below.

4. MEASUREMENT CONDITIONS

When the installation of the CLD elements was completed, measurements of noise from the mitigated bridge were taken on 6th June 2018. Weather conditions were comparable to those of the pre-study in April 2017, see Table 2. From an acoustical point of view, it is assessed that the meteorological conditions for the two measurement times were comparable. All measurements were taken in daytime in dry weather, with background noise from urban activities.

Parameter	April 2017	June 2018
Wind	2-4 m/s, W	<4 m/s, NW
Temperature	7-10 ºC	11-17 ◦C
Clouds	4-7 oktas	1-6 oktas

Table 2. Weather conditions during measurements.

Due to the short distance (approx. 45 m) between noise source and receiver, and the high elevation, it is assumed that the wind speed contribution to the measurement uncertainty was small (7).

Bridge vibration and point mobility were measured on 26 July 2018 under similar temperature conditions.

5. MEASUREMENT RESULTS

5.1 Noise results

Noise was recorded at Pos A using Brüel & Kjær sound level meters BK2250, with maximum useable frequency 3300 Hz, in 24 bit quality. Start and stop timing of train passages on the Old Årsta bridge were detected using an insensitive accelerometer mounted to the underside of the deck, at each end of the bridge. This “train detector” system was recorded at sample frequency 6400 Hz using a laptop computer with a National Instruments data acquisition system. The noise for each train passage was analysed in terms of $L_{Aeq,T}$, where time interval T was the passage time of the steel bridge as identified by the “train detector” system.

Measurements were only taken at times without trains passing on the other tracks of the two Årsta bridges. The background noise was generally 50-60 dB(A), which was always more than 10 dB below the measured train noise. Hence, no correction for background noise was necessary for the overall values.

Passage speeds and noise levels before and after CLD installation are seen in Table 3 and Table 4, respectively.

Run ID	NB1	NB2	NB3	NB4	NB5	NB6	NB7	NB8	Mean
Speed [km/h]	82	84	95	86	87	95	92	87	88
Noise [dB(A)]	81.9	81.7	84.7	81.5	82.4	82.2	82.7	82.2	**82.4**

Table 3. Speed and noise at Pos A from April 2017, before CLD installation. Noise levels are overall LAeq,T [dB(A)] for the passage of the steel bridge.

Run ID	NA1	NA2	NA3	NA4	NA5	NA6	NA7	NA8	NA9	Mean
Speed [km/h]	84	90	90	96	98	93	98	86	84	91
Noise [dB(A)]	72.7	78.0	78.7	75.8	77.2	82.9	79.8	76.6	75.2	**77.4**

Table 4. Speed and noise at Pos A from June 2018, after CLD installation. Noise levels are overall LAeq,T [dB(A)] for the passage of the steel bridge.

The 8 runs before CLD installation showed an arithmetic average of 82 dB, at an average train speed of 88 km/h. The standard deviation was 1.0 dB. A coarse assessment of the associated measurement uncertainty assuming coverage factor k=1.3 (corresponding to 80% level-of-confidence) is then approximately 1.3 dB.

The 9 runs after CLD installation showed an arithmetic average of 77 dB, at an average train speed of 91 km/h. The standard deviation was 3.0 dB. A coarse assessment of the measurement uncertainty using coverage factor k=1.3 (corresponding to 80% level-of-confidence) is approximately 3.8 dB. The measurement uncertainties are in both cases most likely dominated by variations in the noise source, such as wheel roughness, with a minor contribution from atmospheric conditions such as wind (7).

Comparison of the averaged noise levels before and after CLD installation shows an obtained noise reduction of 5 dB.

Similar to Pos A, noise measurements were taken on the facade of a multi-story compartment building at a certain distance from the bridge. Based on arithmetic mean of the measured noise levels during passage, a noise reduction of 5 dB was obtained also in this position.

All steel bridge passage noise spectra are plotted in Figure 6, where continuous lines refer to before CLD installation, and dashed lines are after. The thick red lines are average spectra, before and after CLD installation. It is seen that spectra after CLD installation are generally below those before, for frequencies below approximately 1250 Hz. The reduction is particularly large in the range 400 to 800 Hz. Two of the spectra after CLD installation present an additional peak around 1.6 kHz, possibly due to wheel tread defects. Ignoring these peaks would only affect the reduction estimate by approximately 0.2 dB.

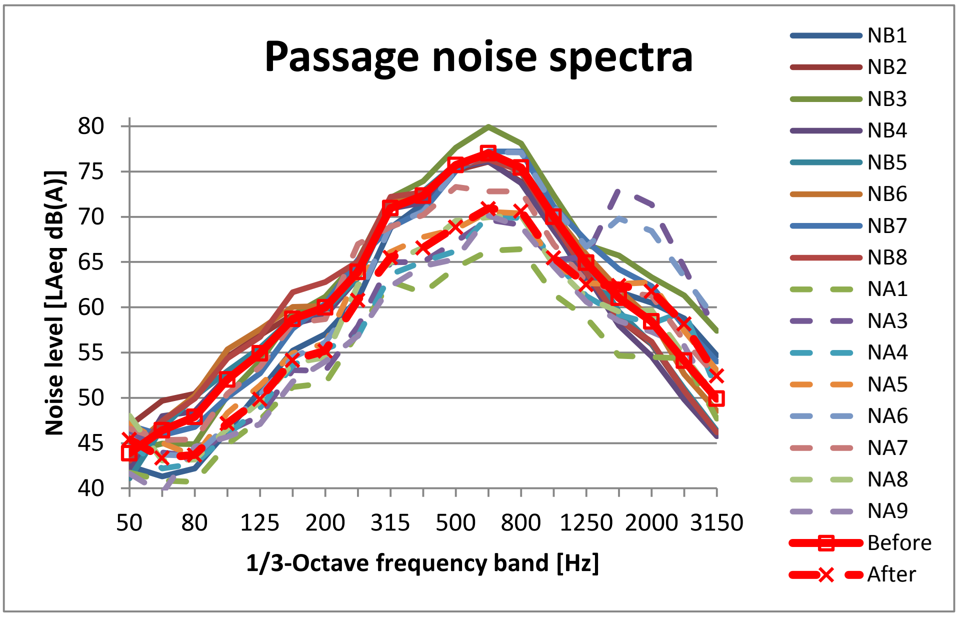

Figure 6. 1/3-octave band spectra at Pos A for all passages.

From the pre-study (1) a maximum potential of 6 dB noise reduction was determined, see also Section 2. In that light, the obtained 5 dB reduction seemed satisfactory.

5.2 Structural damping results

Point mobility measurements were taken before CLD installation 5-7 April 2017, and after CLD installation 26 July 2018. Measurements were taken with a 1.1 Kg PCB086D20 impact hammer with a plastic tip, and a B&K 100 mV/m/s^2 accelerometer. Measurements were taken on all main bridge components, and curve fitted using B&K PULSE Reflex Modal software, MDOF curve fitter type RFP-z.

As an example, the point mobility of the longitudinal girder is shown in Figure 7, for the same measurement position before and after CLD installation. Plate modes appear with natural frequency at about 100 Hz. Clearly, the mobility curve seems to have been reduced in level after CLD installation, and particularly above approximately 300 Hz the peaks have been broadened out due to increased damping. Application of the MDOF curve fitter identified the natural frequencies and corresponding damping ratios as shown in Figure 8. A clear damping increase is seen, from roughly 1% before to 2% after.

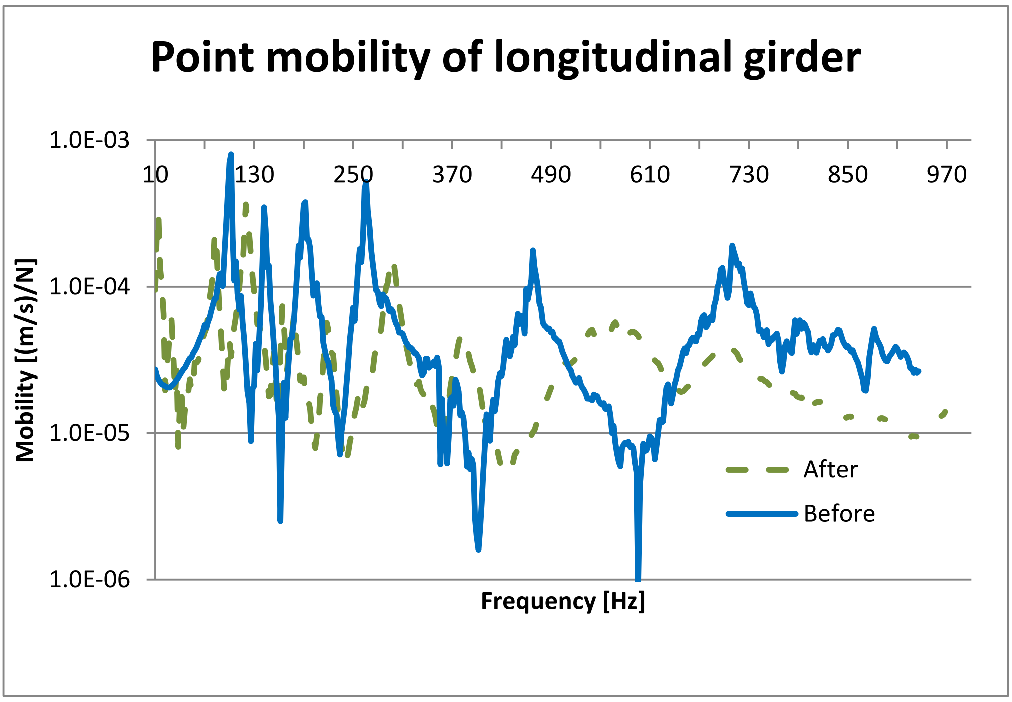

Figure 7. Narrow-band point mobility spectrum of longitudinal girder.Frequency resolution is 2 Hz. No data window was applied. Mobility units are accelerance [(m/s^2)/N). Average of 10 impacts.Curves are before and after CLD installation.

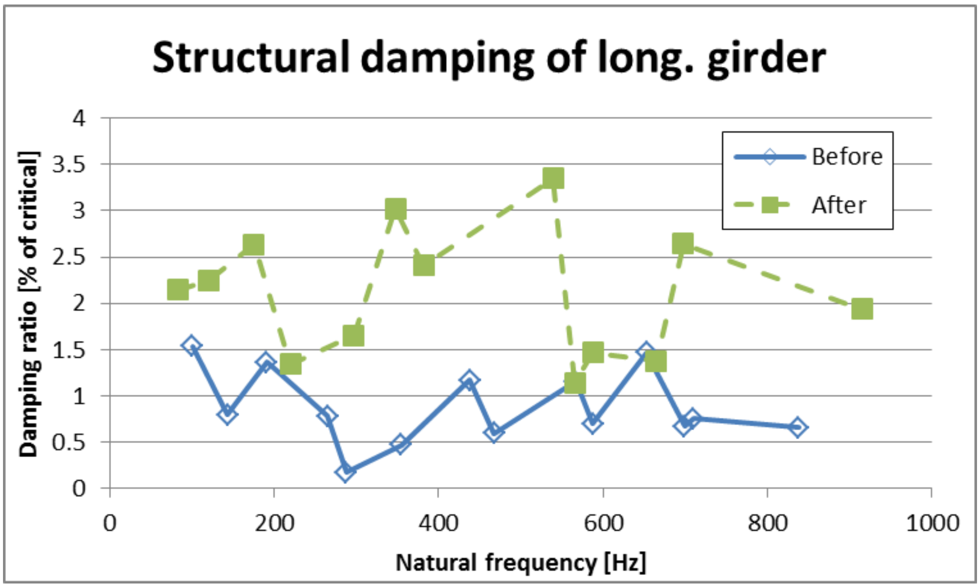

Figure 8. Structural damping ratio of longitudinal girder in per cent of critical damping, before and after CLD installation.

No modal shape information was available from the measurements, since only a single hammer/accelerometer position was investigated. It seems likely, however that modes with practically the same natural frequency and damping ratio before and after CLD installation were not bending modes. Hence, they probably do not have significant noise radiation during vibration.

Measurement results from the transverse plate (not included) showed a significantly increased damping ratio, in line with the longitudinal girder.

Similarly, Figure 9 shows the structural damping for one of the steel deck fields. As the example illustrates, the damping improvement for the deck was found to be less pronounced (about 0.5% increase for 400 to 800 Hz), and less consistent across frequency. This was also found for other deck fields.

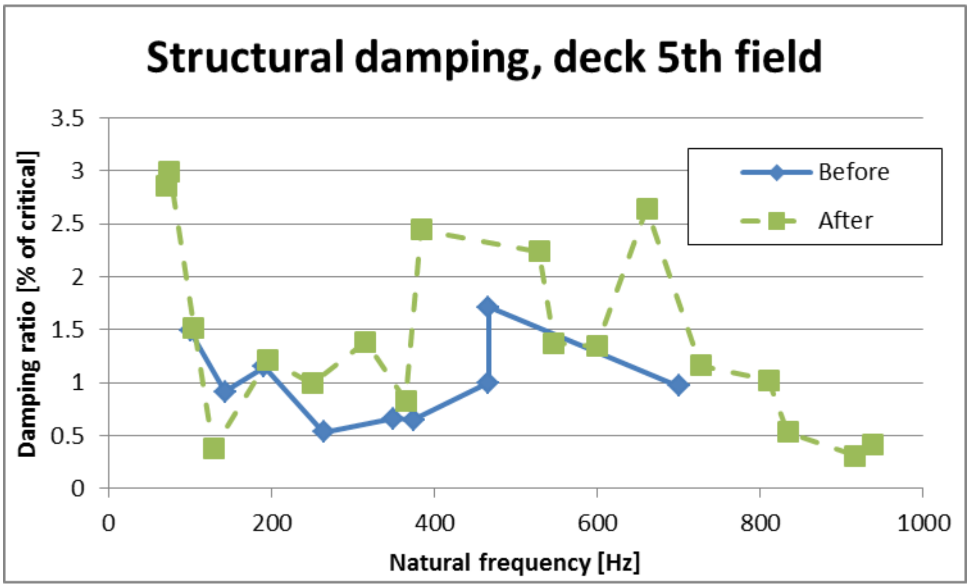

Figure 9. Structural damping ratio of deck field in per cent of critical damping, before and after CLD installation.

6. CONCLUSIONS

Following a comprehensive pre-study (1), a multi-component Constrained Layer Damping (CLD) solution was selected and installed on the Old Årsta railway bridge. The specific CLD design was selected with priority given to consistent damping performance across frequency and environmental temperature.

The installation was achieved without any interruption of the intense railway traffic, and without access to the topside of the deck.

Measurements taken after the CLD installation showed an obtained noise reduction of 5 dB, which was deemed satisfactory. Also, structural dynamic measurements on various bridge components showed a significant increase of the structural damping after the CLD installation.

Furthermore, the pre-study approach combining on-site noise and structural dynamic measurements with numerical modelling was found useful. In combination with climate chamber testing of candidate CLD configurations, this was found to provide a good basis for choosing an efficient noise mitigation strategy for the bridge.

7. ACKNOWLEDGEMENTS

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8. REFERENCES

1. A. Olsen, R.S. Lützen, and S. Holmes, "Noise radiation from steel bridge structure – Old Årsta bridge Stockholm," in *Proceedings of the Internoise* 2017, Hong Kong, China
2. David Thompson, "*Railway Noise and Vibration. Oxford*", Elsevier, (2009)
3. Steve Cox, "Railway noise: some case studies of different problems with different solutions," in *Proceedings of the AusRAIL PLUS* 2007, Sydney, Australia.
4. Railway steel bridges [Internet]. 2019 [accessed 24th January 2019]. Available from: https://sundv.de/wp-content/uploads/2018/03/SV_BridgeDamper_eng_Int.pdf
5. A. Olsen, and R.S. Lützen, "Vibration Damping of air intake filter for gas" engine, using constrained layer damping (CLD," in *Proceedings of Baltic-Nordic Acoustic Meeting (BNAM)* 2016, Stockholm, Sweden
6. Vibratec Akustikprodukter, "Constrained Layer Damping on old steel bridge". [Internet] 3rd October 2018. Available from: https://www.youtube.com/watch?v=n56oSxd3jV0
7. J. Kragh, J. Jacobsen, and B.B. Jessen, *"Ny meteorologisk ramme for måling af ekstern støj fra virksomheder"*, Lydteknisk Institut, Lyngby (1991). Report no. 148 [Danish language]