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Dynamic load monitoring of a concrete bridge using a fiber optic Distributed Acoustic Sensing (DAS) system

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ABSTRACT: In the present study, the impact of dynamic traffic loading in the concrete structure of an existing bridge has been investigated using a Distributed Acoustic Sensing (DAS) system. The dynamic load results in excitation of Eigen Modes (EM) which have been investigated using dynamic strain measurements at various locations simultaneously. The results of the load tests on Amsterdam bridge 705 make an important contribution to the understanding of its structural behavior. The evaluated data can be used to support and verify Finite Element Models (FEM) contributing to ensure the safety of the ageing concrete structure of the bridge. In the face of increasing traffic density and severe traffic loading on existing infrastructure, a safety evaluation based on accurate distributed fiber optic measurements can be an important means to estimate remaining lifetime of the bridge. The concept of the dynamic loading was based on the use of a tram passing by and a well-defined movement of a 36-ton truck. The load applied in this way led to location-dependent small deflection effects recorded as longitudinal strain of the sensing fiber embedded at the underside of the bridge. The laying of the 93-m long sensing fiber in one piece across and along the bridge serves to obtain distributed two-dimensional dynamic strain data. The achieved results demonstrate the capability of the applied system and method to detect dynamic strain signals in the range of a few µm/m at the spatial resolution of 1 to 10 meter along the 93-m long sensing fiber installed on different trajectory of the bridge. The measurements were performed with an inhouse developed DAS system based on Rayleigh scattering.

1 INTRODUCTION

The durability and life time of concrete constructions depend on the material combination used, the application and the corresponding environmental conditions. Therefore, dedicated health monitoring technology and strategy must be optimized for certain type of constructions. For example for concrete structure with steel reinforcement, corrosion of the steel is one of the main causes of degradation of the construction. For the investigation of concrete structures, recent new technologies under development are for example acoustic emission measurement, machine vision for crack pattern identification and other sensors (PZT, FBG etc..) for local strain measurement. To achieve correct information from these sensing technologies, detail understanding of the mechanical properties/model of the concrete construction is essential. A sufficient number of sensing points at the proper locations to provide the correct measurement results is also needed. Permanent condition monitor will require the installation of a large sensor network. Several optical fiber based technology provide the unique feature of sensor multiplexing. The most widely used type of such fiber optic sensor is the Fiber Bragg Grating (FBG). This fiber optic sensing technology is demonstrated for structural health monitoring of bridges by many groups [1]. A few years ago, a new fiber optic sensing technology named DAS (Distributed Acoustic Sensing) was introduced to measure dynamics strain in an optical fiber. This technology combines the standard advantages of fiber optic sensor (small dimension of the optical fiber, unsusceptible to EMI, highly inert of silica fiber to corrosion, low weight, etc.) with the possibility of measurement the mechanical strain along the entire sensing fiber up to a length of tens of km's.

The principle of the DAS technology and the concept design of the system we used are described in Section 2. This system is used for a test campaign of the Bridge 705 in Amsterdam last year. The design of Bridge 705 and the results of Finite Element Modeling are presented in Section 3. An extensive measurement program was prepared an executed (Section 4) and some DAS measurement results are discussed and compared with the FEM analysis in Section 5.

2 RAYLEIGH SCATTERING BASED DISTRIBUTED ACOUSTIC SENSING (DAS)

The Distributed Acoustic Sensing (DAS) technology is based on the measurement of Rayleigh scattering in the sensing fiber. As in the conventional Optical Time Domain Reflectometry (OTDR) technology to check fiber damage, a short optical pulse is launched into the sensing fiber which can be up to a length to tens of km's. The minuscule impurity in the optical fiber will generate different types of scatterings. This technology measures the reflected Rayleigh scattering as a function of the time delay to the input optical pulse. The time delay corresponds to the location of the measurement. A change in signal in the OTDR measurement corresponds in general to a local discontinuity/abnormality of the fiber. In the DAS technology, interferometric technology is used to achieve phase information of the Rayleigh scattering [2, 3]. The TNO DAS configuration is based on a single pulse configuration and the Rayleigh scattering is analyze by a detection interferometer (Fig. 1). Within the H2020 GeoWell project (www.Geowell-h2020.eu) a test setup is realized and demonstrated in different field tests to measure seismic activities. This TNO DAS system consist of:

- A pulse laser system to generate a short optical pulse of tens of ns;
- A splitter to split a small part of the optical pulse to a detector to calculate the time delay of the Rayleigh scattering from the optical fiber. The major part is used to generate the Rayleigh scattering.
- An internal calibration unit including a calibration fiber of ~110 m and a piezo modulator to generate a test strain signal for calibration purpose. The output of the calibration unit is connected to the Fiber Under Test (FUT);
- An optical amplifier (OA) to boost the Rayleigh scattering redirected by the optical circulator (OC);
- A detection interferometer with a channel length of 10 m. The channel length corresponds to the length in the sensing fiber over which the strain is measured;
- A high-speed detector system to measure the input pulse and the interference signal of the Rayleigh scattering;
- A high-speed ADC system and computer to collect and process the data in MATLAB.

The detection interferometer generates a phase signal which corresponds to the length of a 10 m fiber in the FUT. The location is calculated by the time delay. By measuring the change in the phase originating from successive pulses from the same location of the FUT, dynamic length/strain change of the fiber can be determined. To eliminate cross in the Rayleigh scattering, one need to wait until the scattering of the rear end of the FUT is measured by the detector before the next pulse can be started. Hence the maximum length of FUT is related to the repetition rate of the DAS system. Using a 30 kHz repetition rate for the Bridge 705 experiment, even dynamic strain signal in the acoustic domain can be measured over the entire FUT. Therefore, this technology is widely known as Distributed Acoustic Sensing (DAS).

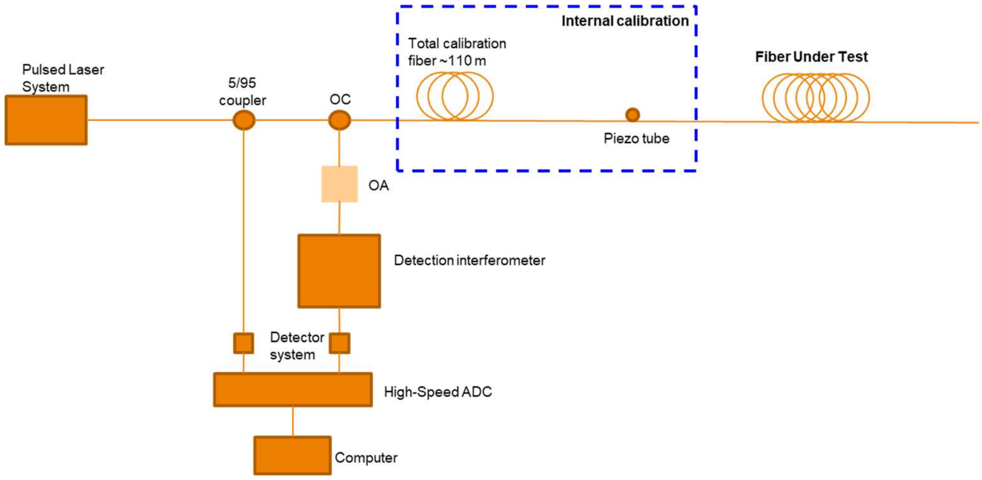

Figure 1. Basic configuration of the TNO DAS system.

The basic output of the DAS measurement is the phase signal of the detection interferometer (expressed in radian) as a function of the location in the FUT (via the time delay referred to the input optical pulse) and time (via the repetition rate of the optical pulses). A phase change of 2π radians corresponds of a length change of half of a wavelength of the light in the optical fiber which is 534 nm. The phase to fiber length change coefficient is 534/6.28 = 85 nm/rad. For a channel length of 10 m over which the length change is measurement, the phase to strain coefficient is 8.5 nε/rad. This coefficient can be used for quantitative analysis of the DAS data.

3 BRIDGE 705 AND RESULTS OF FINITE ELEMENT MODELING

3.1 Structure

Bridge 705 is located in Amsterdam and was commissioned in 1932. The bridge is shown in Figure 2 and is 103 m long with two 13.25 m end spans and five 15.3 m midspans. The deck has a width of 33.2 m and consist of a reinforced concrete slab with a varying thickness between 500 and 650 mm. The deck is supported by V-shaped reinforced concrete columns. In both directions the roadway on the bridge consists of two traffic lanes with a sidewalk on one side. In the middle two tram lanes are present with a sidewalk on both sides.

Figure 2. Bridge 705

3.2 FEM-model

The structural behavior of the bridge was simulated in the finite element program DIANA. The geometry of the model is shown in Figure 3. In DIANA the bridge deck and columns were modelled with shell elements using a 2 x 2 Gauss integration scheme. The concrete material behavior was assumed linear elastic with a Young's modulus $E_c = 38.4$ GPa and a Poisson's ratio $\nu = 0.2$. Unreported displacements based on these properties showed a good agreement with measurements. The abutments and the bottom of the columns were supported in y- and z-direction. The bottom of the columns in the middle two rows in transverse direction was also supported in x-direction. The load in the model consists of the self-weight of the deck and columns and the self-weight of the non-structural (filling) concrete, asphalt, sidewalks and tramway. The extra stiffness of the non-structural (filling) concrete, asphalt and tramway was taken into account by adjusting the Young's modulus locally. The stiffness of the asphalt was assumed as 5.87 GPa at a measurement temperature of 10°C.

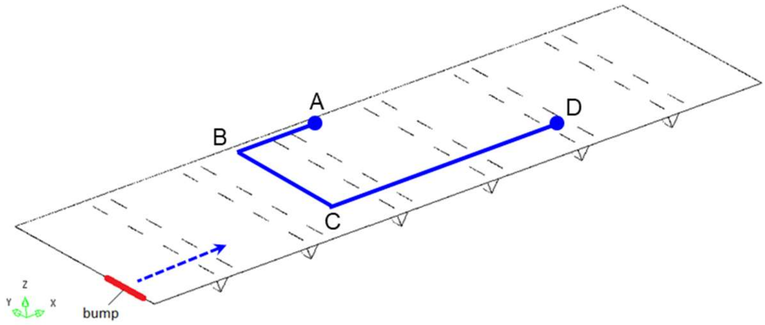

Figure 3. Finite element model of bridge 705. The blue lines represent the optical fiber glued on the bridge and the dotted arrow is the direction of the truck for the dynamic load measurement. A bump can be used to generate a short load peak.

In DIANA a modal response analysis was performed to determine the eigenfrequencies and corresponding eigenmodes. Therefore, the default Arnoldi method based eigenvalue analysis was used to calculate the first 25 eigenpairs. The resulting eigenmodes and eigenfrequencies are shown in respectively Figure 4 and Table 1.

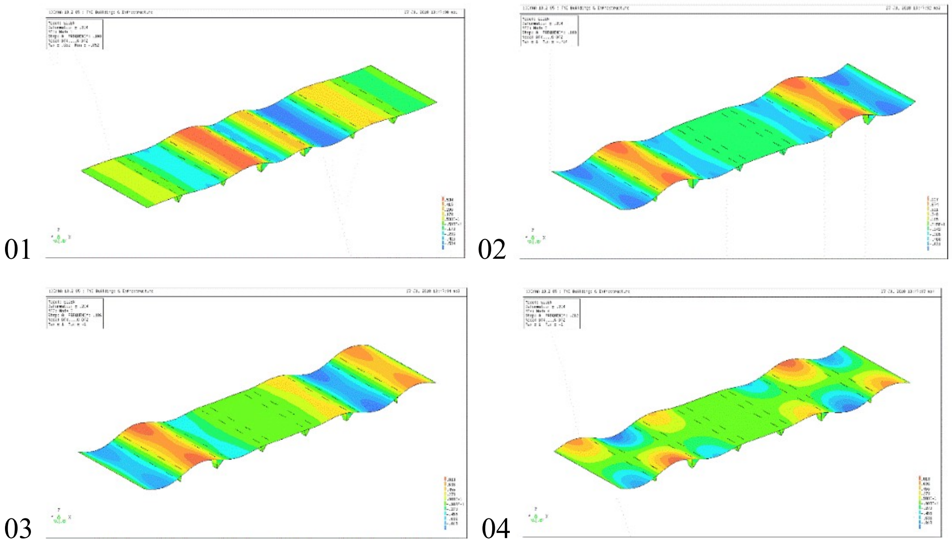
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Figure 4. The first 4 Eigenmodes of the bridge.

Table 1: Eigenfrequencies (Hz)

(1) 3.43	(2) 5.79	(3) 5.88	(4) 6.69	(5) 6.69
(6) 8.76	(7) 9.04	(8) 9.30	(9) 9.30	(10) 9.58
(11) 9.59	(12) 11.87	(13) 11.93	(14) 11.97	(15) 12.00
(16) 12.05	(17) 12.10	(18) 12.21	(19) 12.30	(20) 13.95
(21) 13.95	(22) 14.26	(23) 14.33	(24) 14.49	(25) 15.48

4 TEST SETUP AND TEST PROGRAM

For the measurement of the strain of the bridge construction, a small groove is made in the concrete and a bare sensing fiber (Corning SMF-28 Ultra) is glued into the groove (Fig. 5). The configuration of the fiber glued to the bridge is shown in Figure 3. At both locations A and D, splicing boxes including 10 m of fiber was installed to protect the splice to the connecting fiber to the DAS measurement system.

Figure 5. (Left) Gluing the sensing fiber between position A and D. (Right) Using a truck with constant speed to generate a moving load.

The DAS setup is installed in a cabin next to the bridge. The fiber for internal calibration (see Fig. 1) has a length of 134.6 m. The FUT has a total length of 244.6 m. The first part of the FUT is the lead fiber from the DAS system to the location A on the bridge. After the 10 m fiber in the splicing box at A, the sensing fiber is glue to the bridge. The fiber position of the different part of the fiber identified by the DAS system is shown in Table 2.

Table 2. Position of the different locations along the DAS sensing fiber.

Location	DAS fiber position
Start of FUT	134.6 m
End of lead in fiber at location A (start of 10 m fiber in splicing box)	201.7 m
Position A: Start of short longitudinal path	211.7 m
Position B: Start of lateral path	229.3 m
Position C: Start of long longitudinal path	266.8 m
Position D: End of long longitudinal path	304.2 m
End of FUT (10 m fiber in splicing box + 65 m lead-out fiber	379.2 m

A truck is used as moving load over the bridge (Fig. 5 (Right). The entire test program included the following variables:

- Speed of truck (20 km/h and 50 km/h)
- With and without a bump at the beginning of the bridge (see Fig. 3). The distance between the bump and the lateral path “BC” of the sensing fiber is about 36 m.
- With and without extra static load at different locations at the bridge.

In this paper, only the results of the 3 experiments described in Table 3 are presented.

Table 3. Parameters of the tests.

Test #	Speed of truck	Bump at ~36 m before “BC”	Extra static load
D1	20 km/h	No	No
D2	50 km/h	No	No
D3	20 km/h	Yes	No

5 TEST RESULTS

The rough output of the DAS system is the phase change as a function of fiber location and time. The phase can be converted to strain using the scale factor of 8.5 nε/rad (Section 2). By selecting the time signal from the sensing fiber at a selected location, the phase change as a function of time can be achieved and the PSD can be calculated for spectral analysis.

5.1 3D plot of DAS phase data

A 3D rough phase data plot of test D1 for fiber position between 212 m and 312 m, and measurement time between 15 s and 28 s is shown in Fig. 6 (Left). This corresponds to the moment when the truck passed by the bridge where the sensing fiber is attached. The response to the truck can clearly be observed. Different peaks and dips occur in the rough phase date. They are mainly caused by the optical power fluctuation in the random Rayleigh scattering signal. For optical power lower than a certain threshold level, the system noise becomes dominant which result in those “blind spots” in the measurement. The long longitudinal part of the sensing fiber (between 266.8 m and 304.2 m) is installed in the lane of the moving truck which results in a significant large signal. Using the response of this part of the fiber ((304.2 m – 266.8 m) in ~7s), the speed of the truck in test D1 is estimated to be ~19.2 km/h. From the top view data of test D2 (Fig. 6 (Right)) with a truck speed setting of 50 km/h, the speed is estimated to be ~48 km/h.

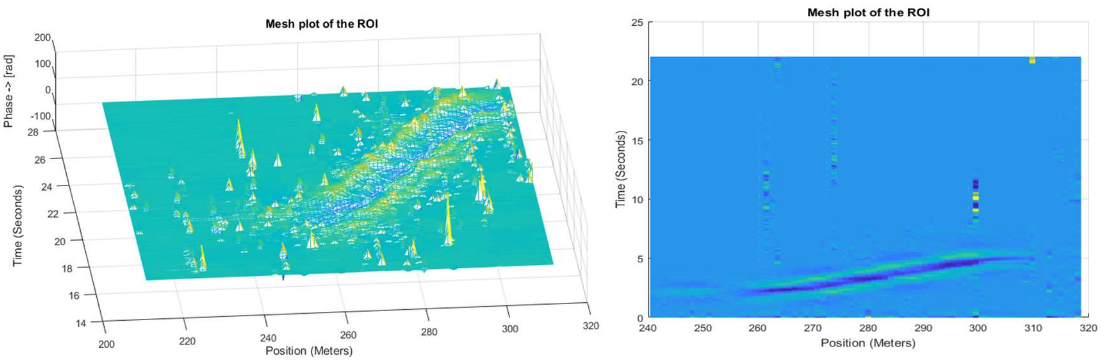

Figure 6. (Left) 3D plot of the phase data of test D1. (Right) Top view of 3D plot of phase data of test D2.

The results D3 with truck speed setting of 20 km/h and a bump at the beginning of the bridge are presented in Fig. 7. The impact of truck passing by the bump to the bridge can be sensed by large part of the sensing fiber at t around 10 s. The highest response is picked up by the long longitudinal fiber path "CD" between 266.8 m and 304.2 m. The smaller response of the lateral path is still visible (see Fig. 8(c)). The passage of the truck over the longitudinal fiber path "CD" shows comparable response as test D1.

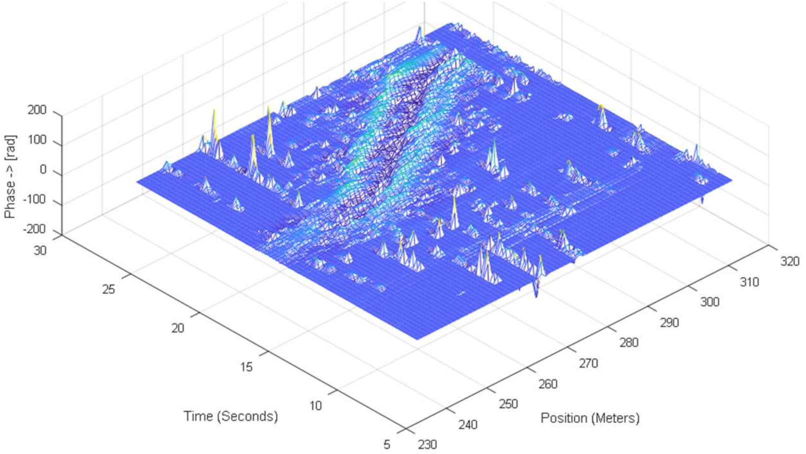

Figure 7. 3D plot of phase data of test D3. The impact of the truck crossing the bump is around t = 10s.

5.2 *Time signal at different locations*

The time signal of the 3 tests are shown in Fig. 8. Due to some special feature in the Graphic User Interface of the software, the time axis is relative. The signal from test D1 from the fiber between 227 m and 230 m (part of lateral path "BC") started at t_0 = 10.5 s. The response of the truck passage can clearly be observed. The duration of the event is about 8 s and the peak to peak signal is about 9 rad which corresponds to 76.5 nε. The long longitudinal path "CD" of the fiber is in the same lane as the moving truck and will experience a large strain. This is shown in the test D2 for the part of "CD" fiber between 280.5 m and 285 m. The presented results started at t_0 = 0 s. The peak to peak signal is ~580 rad which is ~4930 nε. The duration of the load change is shorter due to the higher truck speed. The test D3 data for the fiber between 238 m and 242 m in the lateral path "BC" started at t_0 = 2s. The vibration capture at the last two seconds corresponds to the truck passing the bump which is also shown in the 3D presentation of Fig. 7.

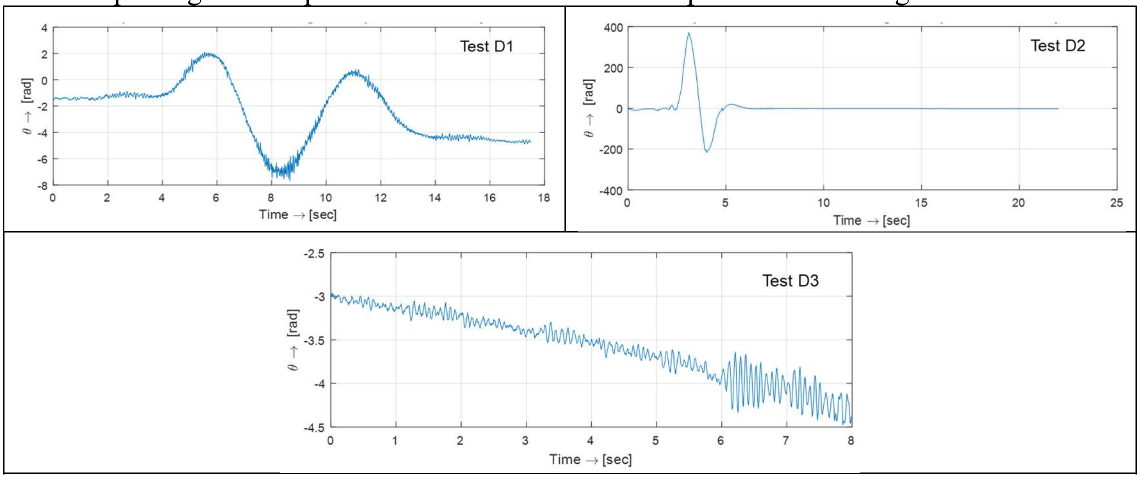

Figure 8. Time signal from different locations of the DAS sensing fiber for the 3 tests.

5.3 *Comparison vibration frequencies: DAS results versus FEM analysis*

PSD analysis can be applied to the time signal to provide information about system noise level and resonance frequency of the construction. The PSD of Figure 8(c) is shown in Figure 9.

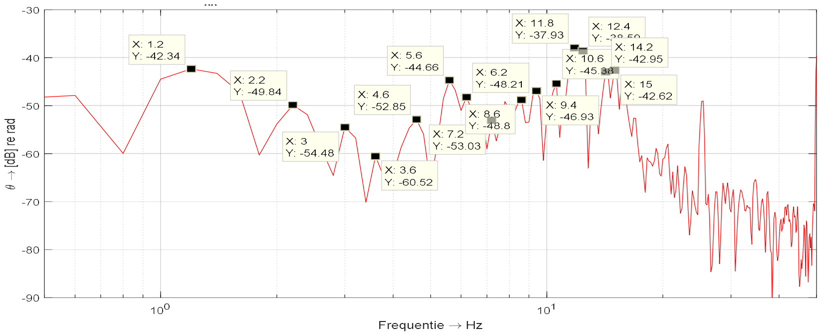

Figure 9. Results of the PSD analysis of the time signal of test D3 in Figure 8(c).

From the data of the 3 tests, the main frequencies in the different paths of the sensing fiber are calculated and summarized in Table 4 and compared with the FEM. Since the excitation of the truck is not calibrated, the information can differ from the eigenmode FEM analysis in Section 3.

Table 4 Measured main frequencies (+/- 0.2 Hz) versus the nearest FEM eigenfrequencies.

D1	Short longitudinal	3,4		6,6	8,2				11,8	15,2
	long Longitudinal	3,2/4,0	5,2		7,8				11,8	
	Lateral	3,6	5,2	6,2	8,4				10,8	
D2	Short longitudinal	3,4	4,2/5,2	6,8	8,8				11,6	13,8
	long Longitudinal	4,0	5,2	7,0			9,4		12,0	
	Lateral		4,8/5,8	7,6				9,8	11,4/12,8	
D3	Short longitudinal	3,2/4,0			7,8	9,0			11,2	15,2
	long Longitudinal	3,2	5,6		8,2				11,4	14,4/15,6
	Lateral	3,2/4,0	5,0	6,4	8,0/8,8				11,6	15,2
FEM		**3,4**	**5,8**	**6,7**	**8,8**	**9,0**	**9,3**	**9,6**	**11,9**	**15,5**

6 CONCLUSIONS AND RECOMMENDATIONS

The installation and application of the DAS system for the monitoring of Bridge 705 is demonstrated. Using a 93-m long sensing fiber, glued to the bridge, different events by a moving truck can be identified. The corresponding strain can be measured dynamically and potentially be used for Weight-In-Motion and traffic (speed) monitoring. FEM analysis of eigenmodes and eigen frequencies are performed and compared to the PSD analysis of the DAS time signal. Several matches are found. Further investigation for optimizing the eigen frequency measurement is required. The current DAS system has a channel length of 10 m. To improve the spatial resolution, reducing the channel length down to < 5 m is desired.

7 REFERENCES

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