Static and Dynamic Bridge Monitoring with Distributed Fiber Optic Sensing

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ABSTRACT

Structural health monitoring (SHM) of bridges and other critical infrastructure is progressively gaining more importance, especially since many bridges in Central Europe and North America are coming to the end of their design life time. Efficient monitoring is therefore necessary to ensure safe operation. In order to measure not only fast changes due to traffic loads but also slow changes caused by temperature or degradation, several different sensor types are usually needed. Distributed Fiber Optic Sensing (DFOS) can provide both static and dynamic information. This article focuses on the monitoring of a steel-concrete composite highway bridge in Austria. Two of the seven spans were equipped with fiber optic sensing cables. By using different DFOS techniques such as Distributed Acoustic Sensing (DAS) and Brillouin Optical Frequency Domain Analysis (BOFDA), both dynamic and static monitoring can be realized seamlessly along the sensing cables. The combination of both fiber optic measurement techniques allows the determination of the vibration behavior of the bridge where not only the eigenfrequencies can be observed, but also slow changes caused by external influences such as temperature. We demonstrate that individual vehicles can not only be identified in DAS measurements, but also characterized in terms of mass and speed. To verify the static and dynamic DFOS results, point-wise sensors such as Robotic Total Stations (RTS) and accelerometers are used as reference.

INTRODUCTION

Due to rising age of bridges not only in Austria but all over the world, many of them have to be under observation in order to ensure safe operation. As Figure 1 shows, in several countries most construction activity regarding bridges has taken place in the 1960s and 1970s, leading to many bridges coming to the end of their design life time by now.

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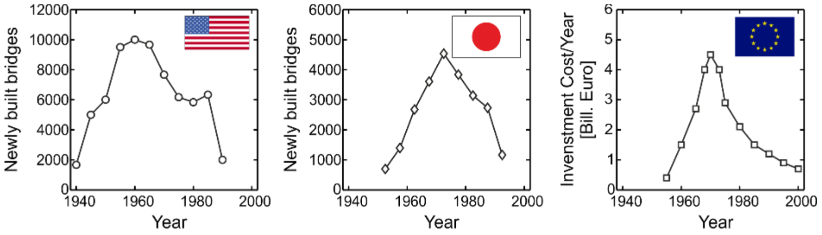

Figure 1. Bridge construction activity in USA [1] and Japan [2] and investment costs in Europe [3].

There are different methods on how bridge monitoring can be performed. Generally, it is distinguished between point-wise and distributed sensing. Suitable point-wise sensors are e.g. accelerometers, which measure accelerations in one or more directions and provide insights into the vibration behavior of the bridge at the designated sensor position. Similar results can be achieved by using Robotic Total Stations (RTS) [4][5], which enable the measurement of absolute displacements in 3 directions. Furthermore, high-speed cameras [6][7] or GNSS sensors [5][8] can be used. But what they all have in common is the drawback of requiring multiple sensors in order to analyze the behavior of the structure.

Latest technologies enable seamless monitoring of entire bridge spans through the use of distributed sensing. These methods range from interferometric radars and profile laser scanners [9] to Distributed Fiber Optic Sensing (DFOS) [10-12]. However, laser scans and radar measurements are sensitive only to line of sight deformations and are therefore dependent on it. Furthermore, line of sight is limited to a small area at any given time. DFOS however can cover several spans with only one sensing element which can be measured seamlessly at the same time. By using two different DFOS methods, short- and long-term deformations can be measured with high accuracy. These methods are described in more detail in the following chapter.

BRIDGE MONITORING WITH DISTRIBUTED FIBER OPTIC SENSING

In recent years, monitoring of both rail and road bridges with distributed fiber optic sensing has become more popular. There are different possibilities of using DFOS for monitoring. For shorter bridge spans, monitoring with Optical Backscatter Reflectometry (OBR) can give accurate results, as shown in [10] and [11]. For larger bridge spans or the monitoring of entire bridges, long range DFOS techniques such as Distributed Acoustic Sensing (DAS) or Brillouin Sensing have to be used. The use of the latter has been described in [12] in 2012 already. So far, DAS has not been applied for bridge monitoring at a larger scale. The combination of the two sensing technologies comes with several advantages since not only long-term changes can be measured but also the dynamic behavior of the bridge can be assessed.

The working principle of distributed fiber optic sensors is pulsed or frequency modulated light coupled into a glass fiber, whereby parts of the induced light get backscattered at every position inside the fiber due to natural impurities. Due to different backscattering effects (see Figure 2), different information can be sensed along the fiber. In case of using Brillouin Analysis (BOTDA or BOFDA), a stimulating continuous wave is sent into the fiber using a loop configuration. This enables the accurate measurement of the unique Brillouin frequency which changes due to temperature or

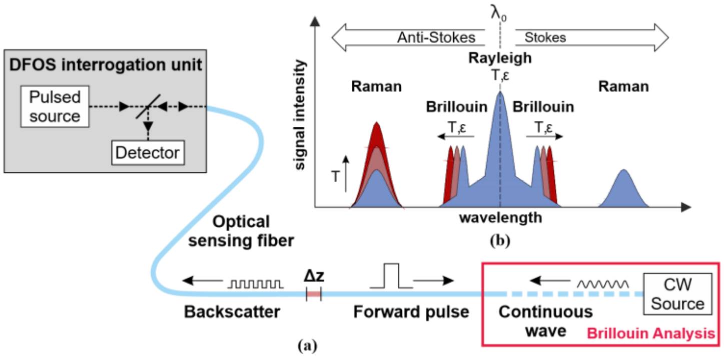

Figure 2. (a) Schematic operating principle of distributed fiber optic sensors, (b) different backscatter components; based on [13].

strain changes. Both the Brillouin and Rayleigh backscatter are sensitive to strain and temperature changes, but still different information can be gained from both. DAS, which uses Rayleigh backscattering, is mainly sensitive to strain changes caused by acoustic signals or vibration along the fiber [14]. Since the acquisition rate can amount up to several kHz dependent on the fiber length, fast strain changes can be measured. This allows insights on the vibration behavior of the bridge. Brillouin sensing, however, measures the unique Brillouin frequency of a fiber, which is changed due to temperature or strain impacts. Since one measurement can take up to several minutes depending on the fiber length, this method is suitable only for measuring long-term changes. More information about different DFOS techniques can also be found in [13] and [15]. Table I shows an overview of the characteristics of both DAS and Brillouin measurements.

TABLE I. COMPARISON OF USED DFOS TECHNIQUES [16][17]

	DAS	**BOFDA**
Backscatter component	Rayleigh	Brillouin
Configuration	Single-ended	Loop
Absolute measurements	No	Yes
Measurand	Strain rate	Strain, Temperature
Spatial resolution	≥ 1 m	≥ 20 cm
Sensing range	Up to 50 km	Up to 80 km

CASE STUDY OF A HIGHWAY BRIDGE

The results shown in the following chapters are derived from measurements carried out at a steel-concrete composite highway bridge in the Austrian alps (Figure 3). The bridge comprises 7 spans and covers a total length of 560 m with pillar heights up to 80 m. The bridge includes two carriageways completely separated from each other in terms of vibration, with three lanes each. Since the bridge was built in the 1960s, monitoring is required in order to assess its structural integrity. Therefore, two of the seven spans were equipped with fiber optic sensors and other measurement devices. The fibers guarantee a seamless monitoring over the entire length, whereas point-wise sensors such as accelerometers and RTS can be used as a selective reference. A schematic representation of the monitored bridge spans is shown in Figure 4.

Figure 3. Highway bridge in the Austrian alps.

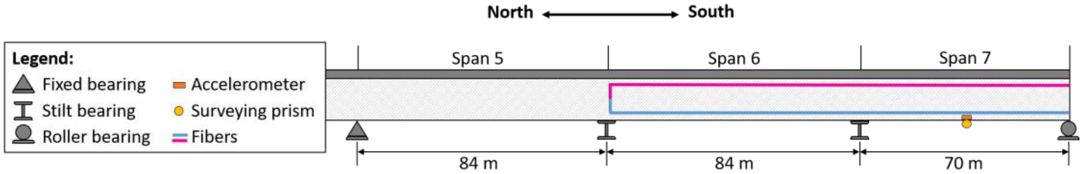

Figure 4. Schematic representation of bridge spans 5, 6 & 7 with mounted sensors.

STATIC MONITORING WITH BRILLOUIN SENSING

In contrast to the DAS measurements, Brillouin measurements can be used to determine seasonal or long-term changes. Both temperature and strain changes can be measured, allowing for a better understanding of the bridge’s behavior and also for recognition of irreversible deformations. Figure 5 shows the temperature impact on the bridge. Due to the structural design and orientation of the bridge, there are situations in which only the lower part of the steel structure is illuminated by the sun. In such situations, temperature measurements show a significant difference between the lower and upper part of the fiber. The resultant effect on the bridge can be seen in the strain measurements, in which the upper part remains relatively constant over the entire bridge spans, whereas the lower part experiences a significant amount of inhomogeneous strain changes.

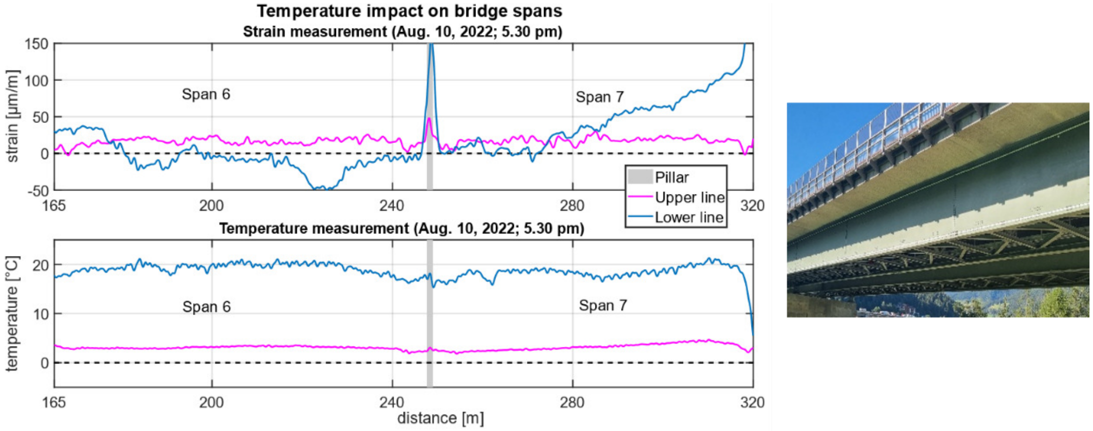

Figure 5. Left: Inhomogeneous temperature impact on bridge spans. Right: Illumination of the lower part only.

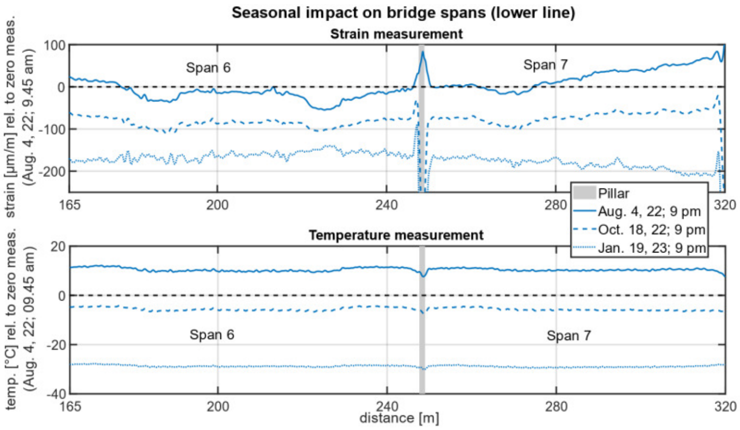

Figure 6. Seasonal temperature and strain changes at the bridge.

Since the epoch-wise Brillouin measurements can always be referred to the zero measurement, seasonal changes can also be derived. Figure 6 shows measurements from summer, autumn and winter at the same time of day. Significant strain changes of the bridge spans can be measured caused by temperature changes.

DYNAMIC MONITORING WITH DISTRIBUTED ACOUSTIC SENSING

In contrast to the Brillouin measurements, DAS measurements allow the acquisition of short-term respectively high frequent changes. Therefore, not only passing vehicles can be measured, but also the vibration behavior of the bridge can be assessed. The native reading of DAS measurements is usually strain rate which can be integrated to strain. Figure 7 shows a waterfall plot of the DAS strain data over a time period of 80 seconds (x-axis) for the upper (0-160 m) and lower (160-320 m) fiber line on the two bridge spans. A difference between the upper and lower line is clearly visible, whereby on the lower line every single vehicle passing the bridge can be detected. The movement along the bridge can clearly be identified, causing positive strain at the vehicle's position and negative strain before and after. The velocity of the vehicles can also be easily calculated from DAS measurement data. The strain behavior along the bridge caused by vehicles is shown in Figure 8, where the upper image represents the strain at two different points in time induced by a passing truck and the lower image the strain caused by a passenger car. The difference between the upper and lower fiber line already visible in Figure 7 is depicted in more detail in Figure 9.

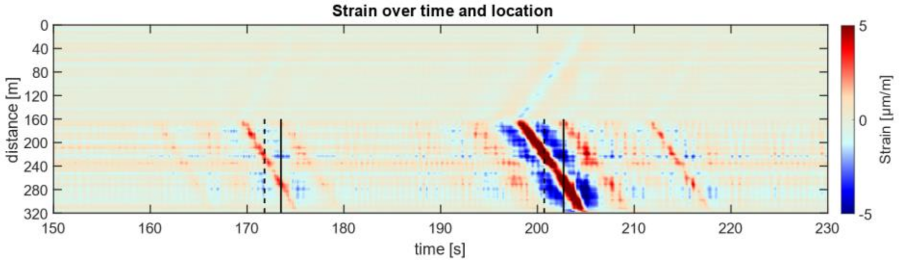

Figure 7. Waterfall plot of DAS strain data, black lines representing data series in Figure 8.

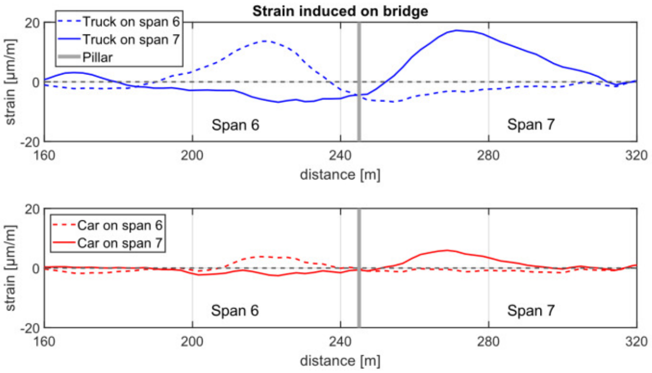

Figure 8. Induced strain on the bridge by different passing vehicles.

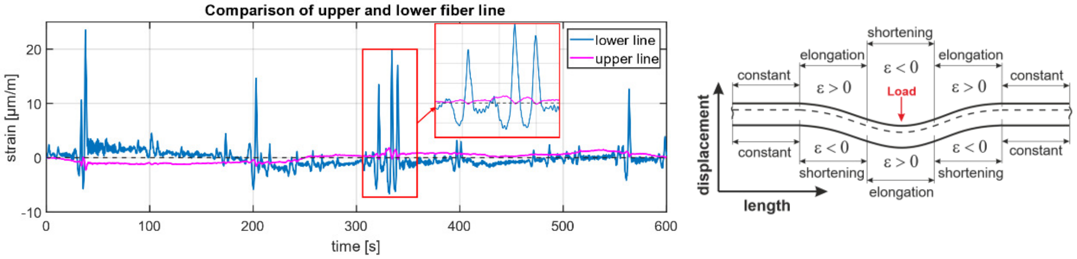

Figure 9. Left: Comparison between upper and lower fiber line. Right: Schematic representation of the relation between displacements and strain along the fiber.

The upper part of the steel structure experiences almost no strain compared to the lower part which results from the higher stiffness in the upper part produced by the concrete carriageway. It should also be noted that the upper line experiences compression in the moment the lower line experiences strain at the corresponding location. This effect is also explained in Figure 9.

In order to verify the DFOS results, point-wise sensors have been installed. Figure 10 shows a comparison with the RTS measurements in the middle of span 7. The strain data calculated from DAS measurements agrees perfectly with the measured deformation of the RTS measurements. Again, it has to be noted that a vertical settlement results in a positive strain change at the lower fiber line.

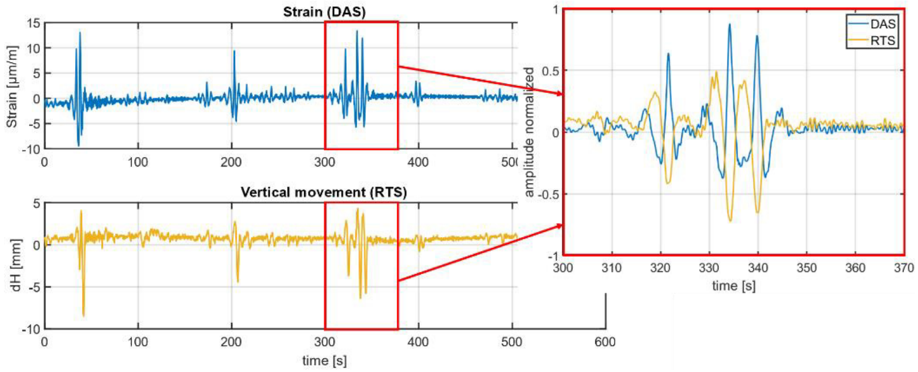

Figure 10. Comparison of DAS strain data with RTS displacements

Furthermore, frequency analysis can be performed on the DAS data in order to obtain information about the vibration behavior. Figure 11 presents the frequency components at 3 points along the fiber, where significant differences can be recognized between the middle of a bridge span and the pillar as well as between the upper and lower fiber line. The distribution of the main frequencies along the bridge spans is shown in Figure 12, where the higher amplitudes in the middle of the spans are clearly visible. As a selective reference, accelerometer data is compared to the DAS data at the corresponding location, where a good agreement of the main frequencies can be observed (Figure 11).

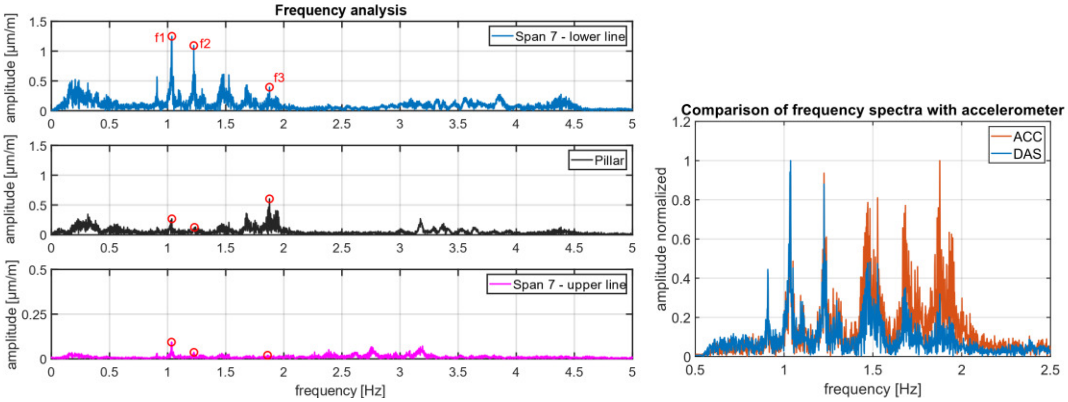

Figure 11. Left: Frequency analysis at different points along the fiber. Right: Comparison with accelerometer at the corresponding location.

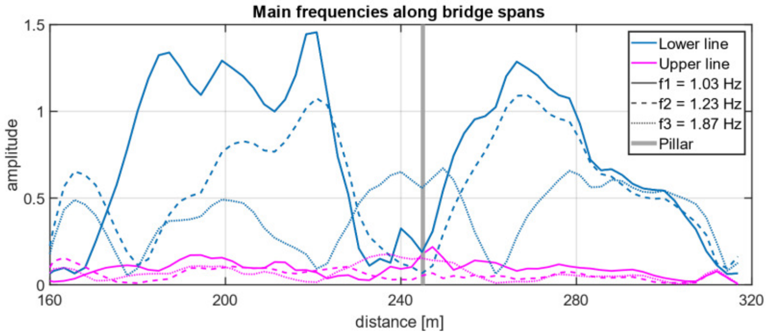

Figure 12. Amplitude distribution of main frequencies along the bridge spans for upper and lower fiber line.

SUMMARY AND OUTLOOK

We have demonstrated that the combined use of different DFOS techniques brings many advantages in bridge monitoring. A seamless monitoring can be performed and the behavior of the bridge in terms of vibration and deformation can be observed. Selective comparisons with point-wise reference measurements have shown the plausibility of the results. Further measurements will complete a one-year cycle and give more information about possible irreversible deformations.

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