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Dynamic Response Monitoring of the Zeeland Bridge Using Distributed Fibre Optic Sensing on Existing Telecom Fibres

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Abstract. This paper presents a pioneering application of Distributed Fibre Optic Sensing (DFOS) technology for the dynamic response monitoring of the Zeeland Bridge, a 5 km long cantilever-balanced prestressed concrete bridge. The study explores the feasibility and potential of using pre-installed single-mode telecommunication fibres, embedded within ducts inside the bridge structure, as a sensing network for large-scale structural health monitoring.

Spatially high-resolution dynamic strain measurements were performed under two distinct loading scenarios: (i) a controlled bridge closure during which a test vehicle was driven over the deck, and (ii) normal operational conditions under ambient traffic. These measurement campaigns allowed for the evaluation of the bridge's dynamic behaviour under both controlled and operational loading conditions.

The DFOS system successfully captured vibration signatures induced by both test and ambient loads, demonstrating its capability to detect dynamic responses over the entire monitored length of the structure. The results highlight the effectiveness of leveraging existing telecom fibre infrastructure for distributed, continuous, and minimally invasive monitoring.

Ongoing data analysis focuses on identifying clear correlations between locally varying structural characteristics of the bridge and its dynamic response. These correlations are expected to provide valuable insights into the bridge's dynamic properties and spatial variability, contributing to an improved understanding of its structural behaviour.

Overall, this study demonstrates the strong potential of DFOS technology combined with existing telecommunication fibres for the long-term monitoring of large-scale civil infrastructure. The proposed approach offers a promising pathway towards more efficient asset management, condition assessment, and maintenance strategies for ageing bridge structures.

Keywords: Distributed Fibre Optic Sensing (DFOS), Structural Health Monitoring, Bridge Dynamics, Telecommunication Fibres, Large-Scale Infrastructure Monitoring

Introduction

Bridges constitute critical components of transportation infrastructure, supporting economic activity and societal mobility. However, a large proportion of bridge networks worldwide is approaching or exceeding its original design life.



By 2025, the average age of bridges in many developed countries is expected to approach 50 years, increasing the risk of structural degradation and functional deficiencies. Aging infrastructure, combined with increasing traffic demand and environmental stressors, poses significant challenges for infrastructure management and public safety. In this context, structural health monitoring (SHM) has become an essential tool for early damage detection, enabling informed maintenance strategies, extending service life, and improving the resilience of transportation networks.

Over the past decades, numerous SHM techniques have been developed to assess the condition and performance of civil infrastructure [1]. Traditional inspection-based methods such as infrared thermography, ultrasonic testing, and ground-penetrating radar are widely used to detect material degradation and structural defects. In parallel, structural health monitoring (SHM) systems based on fixed sensor networks such as accelerometers, strain gauges, and displacement sensors have been extensively developed to enable continuous monitoring of structural responses and dynamic behaviour [2,3]. Modal identification and vibration-based approaches have been widely investigated for bridge assessment and damage detection [4,5]. More recently, advances in data-driven methods and large-scale monitoring strategies have further expanded the capabilities of SHM systems [6,7]. Despite these technological advances, the large-scale deployment of SHM systems remains limited. Conventional monitoring systems typically require dedicated instrumentation, installation efforts, and long-term maintenance, resulting in high costs and limited scalability for large bridge networks. Consequently, many bridges are still primarily inspected through periodic manual inspections rather than continuous monitoring. This gap between available monitoring technologies and their widespread implementation highlights the need for scalable, cost-effective, and minimally invasive monitoring solutions.

A particularly promising approach consists of leveraging existing telecommunication fiber networks as sensing infrastructure. Telecom optical fibers are widely deployed and often co-located with civil infrastructure such as bridges. Repurposing these fibers for sensing applications offers the possibility of transforming existing telecom networks into extensive and cost-effective monitoring systems without requiring additional sensor installations. Although such fibers were not originally designed for sensing and may exhibit imperfect mechanical coupling with the surrounding structure, recent studies have demonstrated their ability to capture relevant dynamic responses of civil infrastructure [8].

In this study, we investigate the potential of distributed fibre optic sensing (DFOS) using existing telecommunication fibres for the dynamic monitoring of the Zeeland Bridge, a 5 km long cantilever-balanced prestressed concrete bridge. Dynamic strain-rate measurements are acquired along a telecom fibre routed within the bridge deck under both controlled loading conditions and normal operational traffic. The objective of this work is to exploit the capability of DFOS to capture the global dynamic response of the bridge.

1. Description of the experiment

The objective of this study is to provide a comprehensive characterization of the global vibrational behaviour of the Zeeland Bridge under operational conditions by identifying its key dynamic parameters, including natural frequencies, damping ratios, and mode shapes, while improving the understanding of support interactions and load transfer mechanisms at mid-span joints.

This work contributes to a refined structural diagnosis and supports the development of long-term monitoring and maintenance strategies within a broader assessment framework aimed at evaluating the bridge's long-term performance. Particular attention is given to potential failure mechanisms such as global and local shear and bending, as well as to key sources of uncertainty, including the remaining prestressing level, creep-induced degradation, and the mechanical behaviour of the substructure (e.g., stiffness, settlement, and tilt), all of which influence load distribution and structural stability [9].

In this context, Distributed Acoustic Sensing (DAS) provides a unique opportunity to acquire large-scale, high-resolution dynamic measurements using existing telecommunication optical fibres installed along the 5 km-long bridge, which consists of 52 simply supported spans supported by 54 reinforced concrete piers. By exploiting ambient vibrations generated by traffic and environmental loads, the DAS measurement campaign enables the construction of a global vibrational identity map of the structure through operational modal analysis. The analysis of distributed strain-rate data allows the extraction of modal parameters for the different spans and the investigation of spatial variability in structural response, offering new insights into the dynamic behaviour of large-scale bridge systems.

2. Material and methods

2.1 DAS Measurement Setup and Principle

To monitor the dynamic behaviour of the Zeeland Bridge under normal operating conditions, a 26-km-long dark (i.e., unlit) telecommunication optical fibre installed along the structure is interrogated using a DAS system. This approach enables the optical fibre to function as a dense array of virtual vibration sensors, providing continuous measurements of the bridge's dynamic response with high spatial resolution. The DAS interrogator unit is connected to the fibre via an operator access point located on the bridge deck.

Continuous measurements have been conducted over a 48-hour period under two distinct operating conditions: (i) normal operational traffic and (ii) a controlled bridge closure during nighttime, during which external disturbances are minimized. These two configurations provide complementary datasets, allowing the characterization of the bridge's dynamic response under both realistic loading scenarios and more controlled conditions. The measurements rely exclusively on ambient vibrations, without the use of any dedicated excitation source, enabling the assessment of the structure under operational conditions.

The DAS system operates by injecting laser pulses into the fibre and analyzing the phase of the Rayleigh backscattered signal [10]. Structural vibrations induce local strain variations, which modify the optical path length and phase of the backscattered light, enabling the reconstruction of a spatially distributed strain-rate field along the fibre representative of the structural response. The measurements are acquired with a sampling frequency of 100 Hz and a spatial resolution of 10 m, providing dense spatial coverage over the close to 5 km long monitored structure.

2.2 Structural Segmentation and Joint Detection

Structural joints along the bridge are identified based on the spatial variation of vibration amplitudes along the fibre.

Two indicators are considered: the temporal root-mean-square (RMS) of the strain-rate signals and the mean absolute amplitude computed at each sensing location. These metrics are used to construct a one-dimensional amplitude profile representing the distribution of vibrational energy along the structure. Structural discontinuities, such as expansion joints or supports, are manifested as local maxima in this profile.

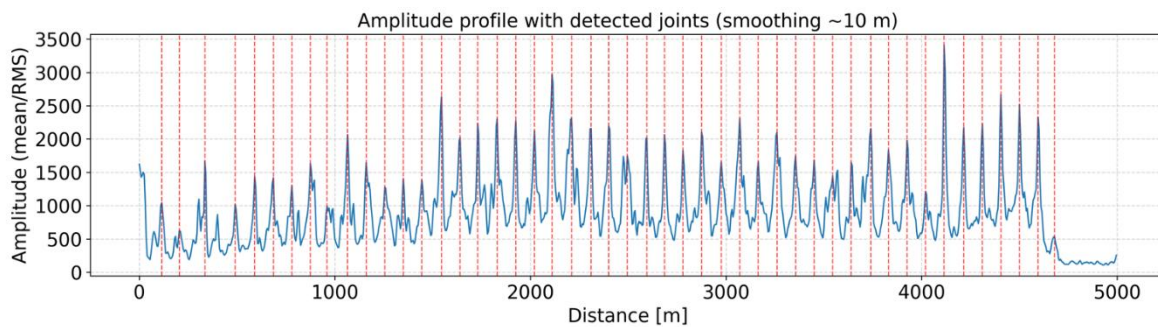


Fig. 1. Location of pavement joints and identification of spans.

To improve robustness, the amplitude profile is first smoothed using a moving average filter over a predefined spatial window, reducing noise-induced fluctuations. Peak detection is then performed using a prominence-based threshold, ensuring that only significant and physically meaningful features are retained. This approach enables an automated and reliable identification of span boundaries along the bridge.

2.3 Signal Processing

To characterize the dynamic behaviour of the bridge, Power Spectral Density (PSD) functions are computed from the raw DAS strain-rate signals [11]. The PSD describes the distribution of signal energy across frequencies and is obtained as the squared magnitude of the Fourier transform. Compared to a standard Fast Fourier Transform (FFT), it provides a smoother and more statistically robust estimate of the spectral content, making it particularly suitable for the analysis of ambient vibrations under operational conditions.

By computing PSDs along the entire sensing fibre, a global vibrational identity map of the structure is constructed [8]. This spatially distributed representation reveals the variation of frequency content along the bridge and highlights its dominant dynamic features.

To extract the main modal characteristics, a Singular Value Decomposition (SVD) of the spectral response matrix is performed. This decomposition isolates the most energetic and coherent components of the structural response, enabling the identification of the bridge's natural frequencies.

The modal properties are further identified using Operational Modal Analysis (OMA), based on the Frequency Domain Decomposition (FDD) method. This technique allows the estimation of natural frequencies and the reconstruction of corresponding mode shapes directly from ambient vibration data [12, 13]. The mode shapes are obtained from the singular vectors associated with peaks in the spectral domain.

The high spatial resolution of DAS measurements enables a detailed reconstruction of these mode shapes along the full length of the bridge, providing insight into both global and local structural behaviour.

In addition to modal analysis, the propagation of traffic-induced vibrations is investigated. Vehicle passages generate wave trains that travel along the bridge deck, both upstream and downstream from structural discontinuities such as expansion joints. These waves exhibit high apparent propagation velocities and gradually attenuate along the structure, indicating energy dissipation and scattering phenomena at structural interfaces.

To quantify these effects, transfer functions are computed between selected locations along the fibre. The transfer function is defined in the frequency domain as: $H(f) = Y(f) / X(f)$ where $X(f)$ represents the input signal measured upstream of a structural feature, and $Y(f)$ corresponds to the output signal measured downstream. High amplitudes of $H(f)$ within specific frequency bands indicate resonance or amplification phenomena, whereas low amplitudes reflect attenuation effects, which may result from structural damping, boundary conditions, or energy scattering at joints.

This combined spectral, modal, and transfer-based analysis provides a comprehensive framework for interpreting the dynamic response of the bridge and improves the understanding of load transfer mechanisms between adjacent spans.

3. Results

3.1 Strain-rate sections

The raw DAS strain-rate data recorded along the instrumented optical fibre provide a direct visualization of the bridge's dynamic response under traffic loading.

Vehicle passages appear as localized disturbances forming clear trajectories in space–time representations, from which travel direction and speed can be inferred. Traffic in both directions (toward Zierikzee and Colijnsplaat) is clearly distinguishable, and vehicle interactions such as crossings or overtaking events can be identified.

Structural discontinuities, particularly expansion joints, are visible as vertical bands of high-amplitude, quasi-stationary signals. These features act as reliable spatial markers, enabling the segmentation of the bridge into individual spans. The raw DAS response thus provides a structural “fingerprint” of the bridge and establishes the basis for subsequent dynamic and modal analyses.

During the nighttime load testing campaign from May 12 to May 13, 2025, the controlled passage of a calibrated truck traveling at approximately 80 km/h from south to north is clearly observed. The transition between normal traffic conditions, bridge closure, and controlled loading is distinctly captured in the data.

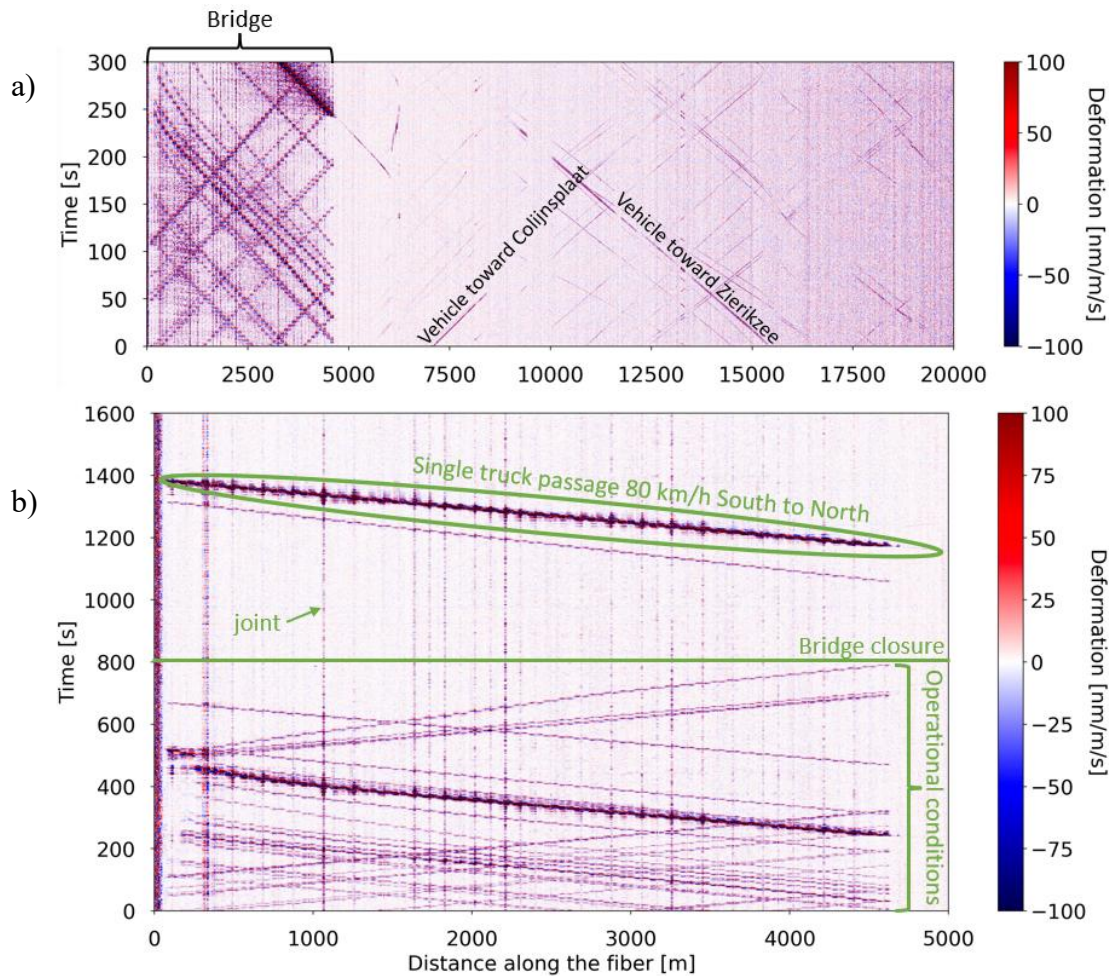


Fig. 3. a) 5-minutes of strainrate data emphasizing the signals of the vehicles on the bridge along the 26km of fiber. b) Illustration of the passage of the calibrated truck traveling at 80 km/h from south to north.

3.2 Spectral Results

By assembling the Power Spectral Density (PSD) functions along the entire optical fibre, a global vibrational identity map of the structure is reconstructed within the low-frequency range (below 2.5 Hz). This representation highlights the first global mode shapes of the bridge and reveals a spatially complex pattern, reflecting localized dynamic variations between different spans (Fig. 4a). It provides an effective tool for tracking the global vibrational behaviour of the structure over time.

Structural segmentation is clearly visible through the presence of vertical bands of very high strain amplitudes associated with the expansion joints. Under traffic loading, modal frequencies appear slightly shifted and less spatially continuous across spans, likely due to nonlinear effects induced by moving loads. These discontinuities complicate modal identification, leading to a focus on the self-weight condition for subsequent analysis.

The spectral decomposition of the response under self-weight conditions, using Singular Value Decomposition (SVD), allows the identification of several dominant natural frequencies representative of the bridge's global dynamics (Fig. 4b).

These frequencies are observed at 0.49 Hz, 0.90 Hz, 1.10 Hz, 1.50 Hz, 3.60 Hz, 3.96 Hz, 4.49 Hz, 5.90 Hz, and 7.23 Hz. In contrast, narrower peaks observed above 10 Hz are less damped and are primarily attributed to traffic-induced excitations rather than intrinsic structural modes.

Modal reconstruction is performed under self-weight conditions to minimize the influence of traffic-induced nonlinearities. However, the presence of expansion joints introduces localized high-amplitude responses that appear as vertical bands in the spectral maps (Fig. 4a). These features can lead to signal saturation and obscure the underlying structural response, thereby affecting the quality of modal identification.

To address this issue, a dedicated preprocessing step is applied to the DAS data to attenuate these high-amplitude contributions. This filtering reduces the influence of structural discontinuities and improves the signal-to-noise ratio, enabling a clearer identification of the bridge's vibration modes. As a result, the mode shapes reconstructed using the Frequency Domain Decomposition method are more robust and representative of the actual structural behaviour.

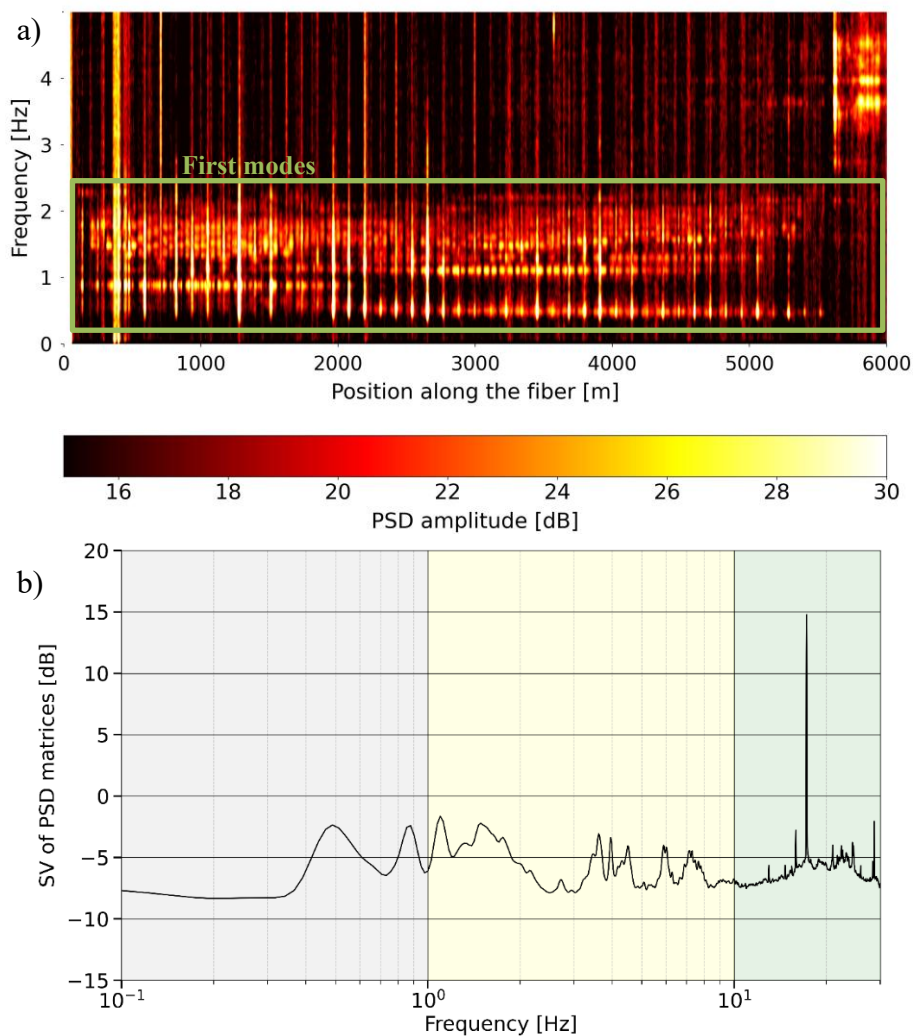


Fig. 4. a) Vibratory fingerprint of the bridge under self-weight conditions. b) Singular Value Decomposition (SVD) computed from one hour of data during the night.

3.3 Experimental mode shapes

A detailed analysis has been carried out on spans 29 to 39 to investigate the spatial variability of the reconstructed mode shapes.

The results show that the type of expansion joint does not significantly influence the measured transverse and vertical modes, as similar modal patterns are observed across the different spans. The reconstructed mode shapes reveal complex spatial behaviours along the bridge. Among the first modes, certain segments between adjacent joints exhibit deformation patterns similar to those of simply supported beams with an apparent hinge located near midspan, corresponding to the central support of each span. This suggests a partial dynamic decoupling between structural segments.

This behaviour can be explained by the heterogeneous distribution of mass and stiffness along the bridge, resulting from variations in structural inertia and boundary conditions, which introduce localized dynamic effects. A significant spatial variability of deformation patterns is observed along the structure, highlighting the heterogeneous nature of the boundary conditions. These results emphasize the strong influence of support stiffness, foundation behaviour, and joint mechanics on the modal response of individual spans.

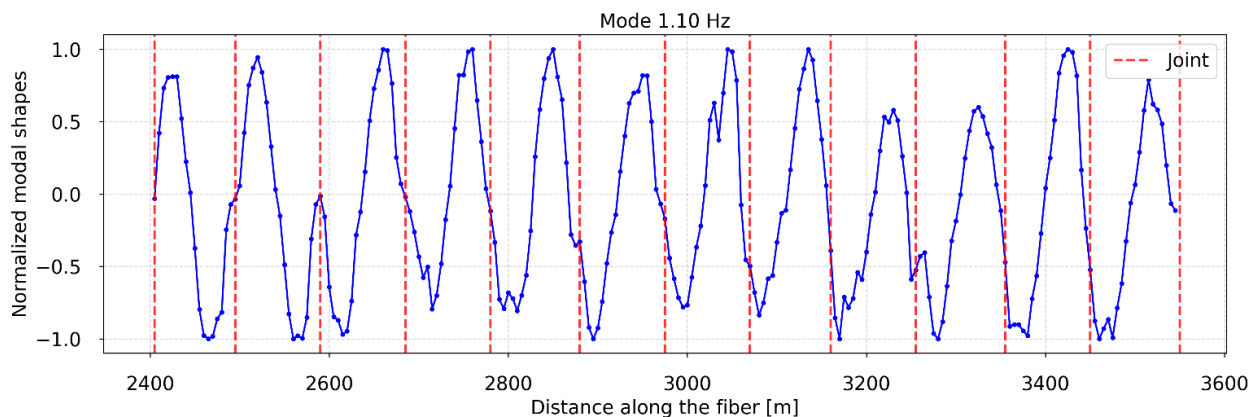


Fig. 5. Example of one experimental modal shape (span 29 to 39).

3.4 Transfer functions

Transfer function analysis has been performed to investigate the dynamic influence of bridge piers on wave propagation and vibration characteristics. The results show a consistent amplification of low-frequency components in the range of 2–5 Hz at pier locations (Fig. 6).

The observed frequency range suggests that pier-related modes may interact with the global and local modes of the bridge deck. Such interactions are likely to contribute to the nonlinear effects identified in the modal reconstruction, particularly in terms of frequency shifts and spatial discontinuities between spans.

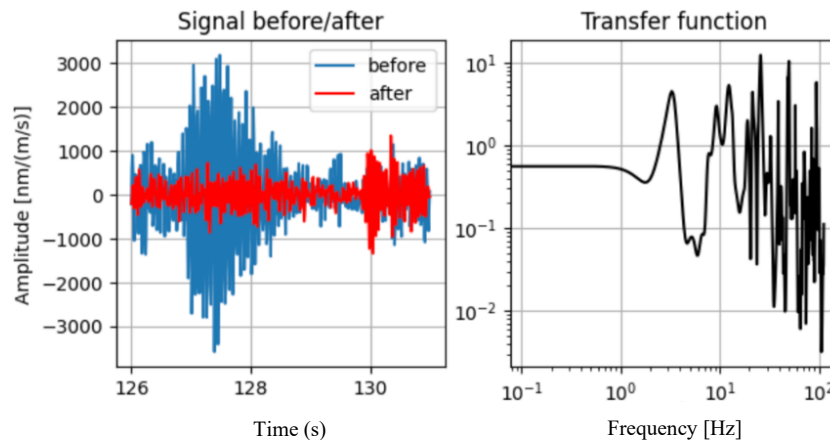


Fig. 6. Example of a temporal signal before and after a pier, and the corresponding support transfer function.

These findings highlight the importance of accounting for substructure dynamics in the interpretation of distributed vibration measurements. The use of transfer functions provides valuable insight into the frequency-dependent filtering and amplification mechanisms occurring at pier locations, improving the overall understanding of load transfer and dynamic coupling within the bridge system.

4. Conclusions

The measurement campaign conducted on the Zeeland Bridge has provided high-resolution, spatially continuous strain-rate data over several kilometers, enabling an unprecedented observation of the structure's dynamic behaviour under both operational and controlled conditions. The analysis of raw data has revealed clear traffic signatures, enabling vehicle tracking, speed estimation, and structural segmentation through the identification of expansion joints. Operational Modal Analysis has allowed the identification of the bridge's main natural frequencies and the reconstruction of its global mode shapes. The results highlight complex and spatially variable dynamic behaviour, strongly influenced by boundary conditions, joint mechanics, and substructure interactions.

Overall, this work confirms that DAS-based monitoring using pre-existing telecom fibres provides a scalable, minimally invasive, and cost-effective solution for monitoring large infrastructures. The ability to capture both global and localized dynamic features opens new perspectives for continuous monitoring, early damage detection, and improved asset management of aging infrastructure.

Future work will focus on further investigating nonlinear effects and long-term structural evolution by coupling the experimental data with a numerical model of the structure.

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