

SMAR 2026 - 8th International Conference on Smart Monitoring, Assessment and Rehabilitation
of Civil Structures

Interpreting InSAR-Derived Bridge Displacements through a Calibrated Finite Element Model

Riccardo Liuzzo^{a,*}, Andrea Brasca^a, Gaia Celli^a, Pier Francesco Giordano^a, Maria Pina
Limongelli^a, Andrea Piscini^b

^a*Department of Architecture, Built environment, and Construction engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133
Milan, Italy*

^b*SINA S.p.A., Viale Isonzo, 14/1, 20135 Milan, Italy*

Abstract

Spaceborne Interferometric Synthetic Aperture Radar (InSAR) is increasingly used for the long-term monitoring of civil infrastructures, enabling the reconstruction of displacement time histories over multi-year periods and extended spatial domains, without dedicated on-site instrumentation. However, the structural interpretation of InSAR-derived displacements remains challenging. The reconstruction of displacement components requires combining measurements from different acquisition geometries and adopting simplifying assumptions on structural behaviour, which may introduce uncertainties and potential bias. In addition, structural displacements reflect the combined influence of environmental actions, structural configuration, restraint conditions, and, where present, anomalous ongoing phenomena. This study examines this issue for the A21 Po River Bridge, a prestressed-concrete Gerber viaduct in northern Italy. The InSAR-derived time histories indicate a predominantly thermally driven longitudinal response, with displacement patterns varying along the bridge and influenced by the restraint conditions at the supports. A Finite Element (FE) model was calibrated through experimentally identified modal frequencies and used to simulate the bridge thermal response. The comparison between measured and simulated displacements shows good agreement in terms of spatial distribution and temporal evolution, supporting the proposed interpretation of the InSAR data.

© 2026 The Authors. Published by ELSEVIER B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of SMAR 2026 Organizers

* Corresponding author.

E-mail address: riccardo.liuzzo@polimi.it

Keywords: Structural Health Monitoring; InSAR; Remote sensing; Acceleration; Finite Element; Bridge

1. Introduction

The condition assessment of existing bridges has received increasing attention in recent years, and a wide range of Structural Health Monitoring (SHM) techniques is currently available to support engineers and infrastructure managers in the interpretation of structural behavior under service conditions (An et al., 2019; Ivanov, 2026; Karakostas et al., 2024). Within this broad framework, a common distinction can be made between dynamic and static monitoring approaches. Dynamic monitoring typically relies on vibration measurements to identify modal parameters that are sensitive to variations in stiffness and boundary conditions, thus providing indirect information on structural condition (Fritzen, 2005; Hsieh et al., 2006). Static monitoring, by contrast, focuses on quantities that evolve more slowly over time and can therefore provide a more direct description of deformation processes and of the structural response under operational conditions and environmental actions (Baraccani et al., 2017; Lanata & Grosso, 2006; Yang et al., 2024). Among static monitoring techniques, spaceborne Interferometric Synthetic Aperture Radar (InSAR) has attracted growing interest in recent years, as it enables the reconstruction of displacement time histories over multi-year observation periods and extended spatial domains without the installation of dedicated instrumentation on-site (Crosetto et al., 2016; Dinh et al., 2020; Raventós et al., 2017). Its practical accessibility has further increased with the European Ground Motion Service (EGMS), the Copernicus service that provides freely available ground-motion products derived from Sentinel-1 data across Europe (Crosetto et al., 2022; Hrysiewicz et al., 2024). These characteristics make InSAR attractive for the monitoring of large infrastructures, for which continuous dense instrumentation is rarely feasible. At the same time, the interpretation of InSAR measurements for infrastructure monitoring is not straightforward. Measurements obtained from satellite interferometry are displacements projected along the satellite Line of Sight (LOS), which does not generally coincide with the directions of structural motion, and are only available for Persistent Scatterers (PSs), targets that provide sufficiently stable radar backscatter over time. To overcome this limitation, ascending and descending datasets are commonly combined to enable the reconstruction of structural displacement components. However, this procedure requires careful spatial and temporal alignment between independent datasets and is inherently affected by processing choices and simplifying assumptions (Giordano, Kamariotis, et al., 2025; Liuzzo et al., 2025). In particular, the inversion of LOS measurements is an underdetermined problem unless additional constraints are introduced. A common approach consists in neglecting one displacement component, often assumed to be negligible based on prior knowledge of structural behavior. In the case of bridges, such assumptions typically rely on the expected kinematics dictated by the structural scheme, boundary conditions, and load distribution. Depending on the case, these assumptions may concern the dominant direction of motion, the portion of the structure effectively involved in the response, or the role of restraint conditions in shaping the deformation induced by external actions. However, these simplifications may not always be valid and may lead to biased or incomplete interpretations of the measured displacements. In this context, numerical models can support the interpretation of InSAR-derived measurements, for instance through calibrated Finite Element (FE) models updated using available monitoring data.

In this paper, the A21 Po River Bridge, a prestressed concrete highway viaduct in northern Italy characterized by a Gerber-type structural scheme, is investigated as a case study. The bridge consists of multiple spans, including cantilever spans supported by piers and suspended segments. The study aims to quantify the interaction between adjacent spans under thermal dilatations and to assess whether the displacement patterns inferred from InSAR measurements are consistent with the expected structural response. To this end, a FE model is developed for a representative portion of the bridge and calibrated using modal frequencies identified from on-site accelerometer measurements. The calibrated model is then employed to simulate the displacement response under thermal loading. The numerical results are compared with displacements reconstructed from EGMS data over the 2019–2023 period.

The remainder of the paper is organized as follows. Section 2 introduces the case study, the monitoring data, and the FE model adopted for the analysis. Section 3 presents the model calibration and discusses the comparison between InSAR-derived and numerically predicted displacements under thermal loading. Section 4 summarizes the main conclusions of the study.

2. Case study

2.1. The A21 Po River Bridge

The case study concerns the A21 Po River Bridge, a highway bridge currently in service along the A21 Piacenza-Brescia motorway in northern Italy. Built in 1968, the bridge consists of 41 spans, with a total length of 1673.5 m. Its superstructure is composed of prestressed-concrete Gerber beams supported by cast-in-place piers, and the deck axis is rotated by approximately 35° anticlockwise with respect to the East-West direction.

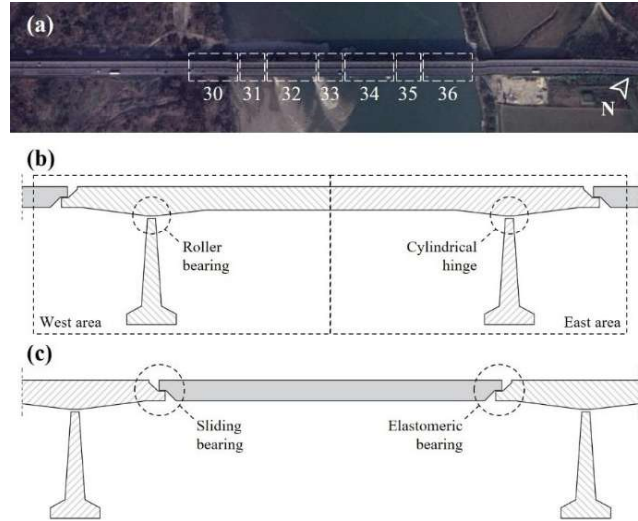


Fig. 1. The A21 highway Po River Bridge. (a) Plan view of the investigated deck segment. Schematic representation of (b) a main cantilever span and (c) a suspended span.

The analysis presented in this paper focuses on the main river crossing, comprising the deck portion extending from Span 30 to Span 36 (Fig. 1a). This segment is supported by eight piers spaced at regular 61.5 m intervals, for a total length of 430.50 m. The viaduct follows a conventional Gerber configuration, in which each pier supports two cantilever arms extending in opposite directions. This arrangement defines a sequence of repeated structural modules, each formed by a main cantilever span and the suspended span connected to it. Each main span is considered here as composed of two distinct portions, corresponding to its western (W) and eastern (E) halves, as shown in Fig. 1b. At the pier locations, the cantilever beams are connected through two different support types: a roller bearing on the west side, which allows longitudinal movement, and a cylindrical hinge on the east side, which restrains horizontal translation while allowing rotation. The suspended spans (Fig. 1c), are instead connected to the adjacent cantilevers through different end conditions, with one side supported by a sliding bearing and the other by an elastomeric bearing. Dynamic monitoring of the bridge relies on 100 triaxial MEMS accelerometers installed in 2020 on each span along the monitored deck segment, covering Spans 26 to 36. Temperature records were obtained from the ARPA Lombardia portal and collected from the “CREMONA v. Gerre Borghi” meteorological station, which provides continuous measurements over the investigated period.

2.2. Analysis of InSAR displacements

The analysis of the static response of the bridge relies on EGMS data available for the viaduct over the 2019-2023 period. The datasets were imported into a GIS environment to inspect the distribution of PSs on the structure and to exclude those located outside the bridge footprint, both in plan and elevation. Among the available products,

EGMS_L2a_015_0265 (hereafter Asc015) and EGMS_L2a_168_0806 (hereafter Dsc168) were selected for the analysis, as they provided the highest number of scatterers over the investigated segment, including 200 PSs in total, of which 74 belong to the ascending orbit and 126 to the descending one. The resulting spatial coverage is generally dense and regular along the bridge, with the exception of zone 36W, where PSs from both acquisition geometries are not simultaneously available. Longitudinal and vertical displacement components were reconstructed by combining Asc015 and Dsc168 measurements under the assumption of negligible transverse motion (Giordano, Kwapisz, et al., 2025).

The present study focuses on the longitudinal response of the bridge. The reconstructed time histories, shown in Fig. 2, exhibit a clear seasonal oscillation over most of the segments investigated. This pattern is particularly evident in the western halves of the main spans and in the suspended spans, where the displacement amplitudes are larger and more regular, whereas the eastern halves generally display a smaller amplitudes and a less pronounced seasonal trend. The comparison with air temperature records (see Fig. 2d) indicates that the observed response is predominantly thermally driven. In particular, the western portions of the main spans exhibit a clear negative correlation with temperature, with negative longitudinal displacements during the warmer months (corresponding to movements in the Piacenza direction, according to the adopted sign convention) and the opposite trend during colder periods. This behaviour is consistent with thermal expansion and contraction occurring under boundary conditions that allow longitudinal movement. In contrast, the eastern portions of the spans show limited displacement amplitudes and a weaker correlation with temperature. This is consistent with the presence of hinge connections that restrain longitudinal displacements, thereby reducing the observable thermal response in these regions. A further insight is provided by the comparison between the suspended spans and the adjacent western portions of the main spans. The displacement amplitudes of the suspended spans are comparable to those of the neighbouring cantilever segments, whereas a larger response would be expected if the spans were behaving independently under thermal loading. This observation suggests that some degree of interaction exists between adjacent spans, indicating that the structural response cannot be fully described as a set of independent elements.

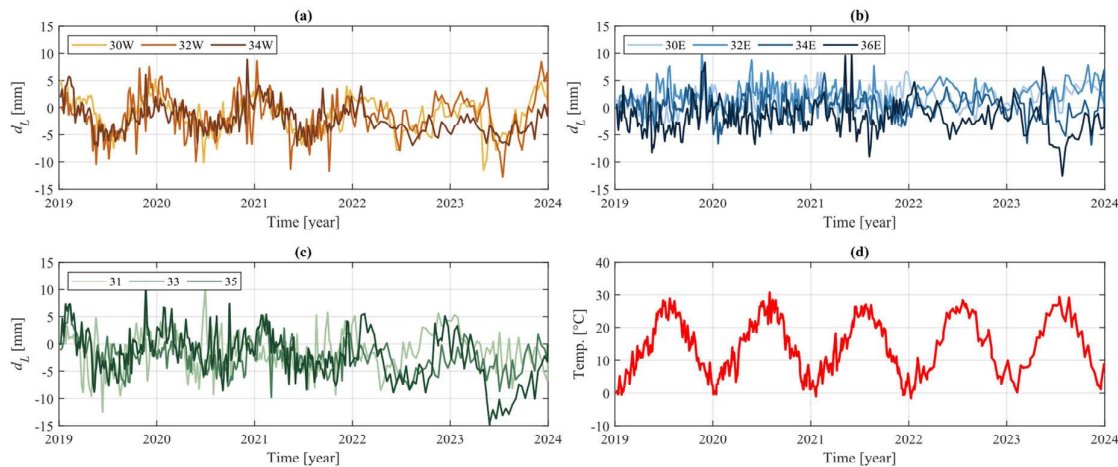


Fig. 2. Longitudinal displacement time histories for the (a) western and (b) eastern halves of the main spans and (c) suspended spans. (d) Temperature records.

2.3. FE model

The FE model of the bridge was developed in MIDAS Civil NX to reproduce the response induced by thermal actions and therefore to support the interpretation of the InSAR-derived displacements. The model was first defined for a representative Gerber module, comprising one main cantilever span and the suspended span connected to it (Fig.

3). This module was then repeated to reproduce the investigated bridge segment. The geometric definition was based on the available design documentation and on the surveyed characteristics of the analysed portion, while the mechanical properties assigned to the structural elements were derived from on-site tests. The main deck members, crossbeams, and piers were modelled using beam elements. The slab contribution was incorporated through an equivalent composite beam–slab section accounting for its effect on both flexural and torsional stiffness. To preserve the in-plane stiffness of the deck, rigid constraints were introduced at the crossbeam locations. A C39/47 concrete class was adopted for the beams and crossbeams, whereas the piers were assigned a C25/30 concrete class. As for support device, the four connection typologies identified on the bridge were represented through equivalent translational and rotational springs. Since the piers are founded on piles of approximately 50 m depth, providing high stiffness against both translations and rotations, the pier bases were modeled as fixed supports. Once the model of the investigated segment had been assembled through the repetition of the representative module, additional spans were included at both ends to reproduce the actual boundary conditions. In particular, two spans were added on the western side, where the structural geometry remains unchanged, together with the adjacent eastern spans, which differ in beam length and pier cross-section.

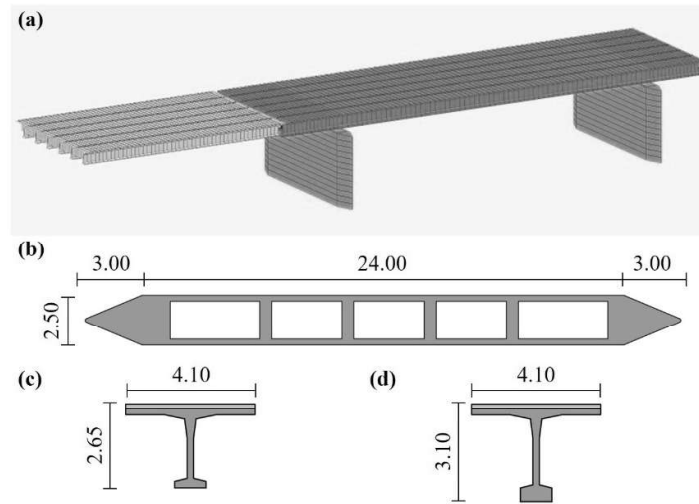
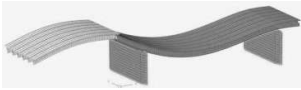
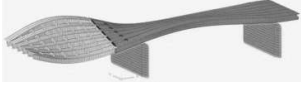


Fig. 3. (a) FE model of the representative Gerber module. Transversal sections of the (b) piers, (c) suspended spans, (d) main spans; all the measurements are in meters.

3. Results

Operational Modal Analysis (OMA) was conducted on ambient vibration measurements collected by the monitoring system using an automated pipeline based on the Stochastic Subspace Identification (SSI) method (Morleo et al., 2025). The analysis was carried out for each span, yielding consistent estimates of the modal frequencies across the investigated segments. The frequencies of the first three global modes were used as reference targets for the calibration of the FE model. The calibration was carried out through an iterative update of the stiffness parameters assigned to the support devices. Initial stiffness values were selected based on technical documentation and literature, and subsequently refined within physically plausible ranges to minimize the discrepancy between the experimentally identified and numerically predicted modal frequencies. As shown in Table 1, the calibrated model reproduces the identified modal frequencies with satisfactory agreement for all selected modes, although a higher discrepancy is observed for the first mode (approximately 13%). The calibrated parameters were adopted for the full model of the bridge segment obtained by repeating the representative Gerber module.

Table 1. Comparison between experimentally identified and numerically predicted modal frequencies of the representative Gerber module.

Mode No.	Mode shape	Measured frequency [Hz]	Computed frequency [Hz]	Difference [%]
1		1.5	1.7	13.3
2		2.6	2.7	3.8
3		3.6	3.6	0.0

Following, thermal analyses were performed on the calibrated FE model to simulate the structural response under temperature variations. Air temperature records were used to define a representative seasonal thermal history for the deck. Longitudinal displacements were extracted at the same locations adopted in the InSAR processing, enabling a direct comparison between model predictions and observations. As shown in Fig. 4, the FE model captures the main features of the InSAR-derived response: the western halves of the main spans exhibit regular seasonal longitudinal oscillations with relatively large amplitude, whereas the eastern halves show a reduced response, consistent with the restraining effect of the cylindrical hinges. The suspended spans display a seasonal evolution comparable to that of the adjacent western portions of the main spans. Up to this point, the FE results were evaluated at the geometric centroid of each zone. In the following, the response is instead evaluated at the centroid of the PSs within each zone, to ensure consistency with the spatial sampling of the InSAR data. The effect of the adopted spatial reference is illustrated in Fig. 5 for the eastern zones, where the proximity of the hinge makes the predicted longitudinal displacement highly sensitive to the evaluation point. In particular, when the geometric centroid and the PS centroid are located on opposite sides of the restraint, the FE response may differ significantly in both sign and amplitude. When the FE displacements are referred to the centroid of the PSs used in the InSAR analysis, the agreement with the measured time histories improves markedly. In this situation, the comparison supports a thermally driven response with interaction between adjacent spans, in line with both the InSAR observations and the calibrated FE model.

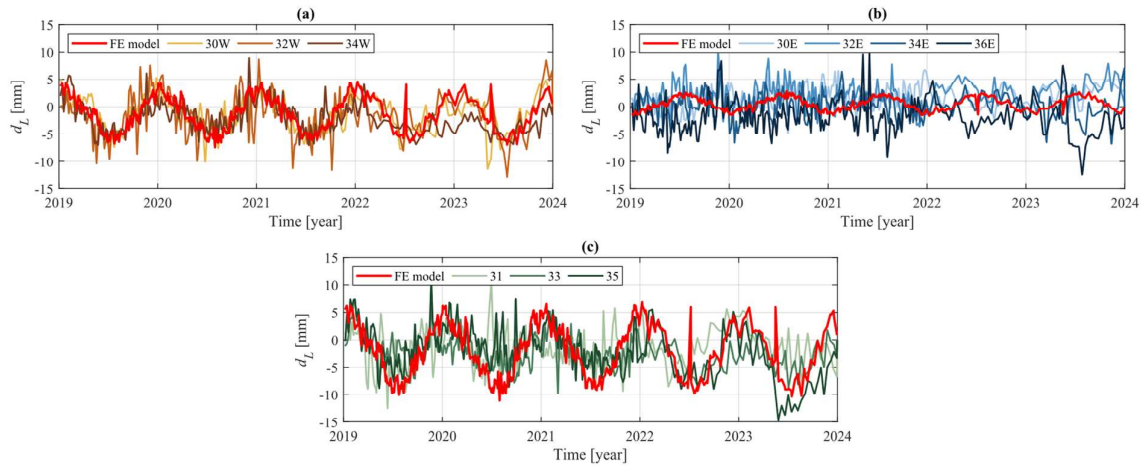


Fig. 4. Comparison between InSAR-derived longitudinal displacements and FE predictions extracted at the geometric centroid of each zone: (a) western zones, (b) eastern zones, (c) suspended spans.

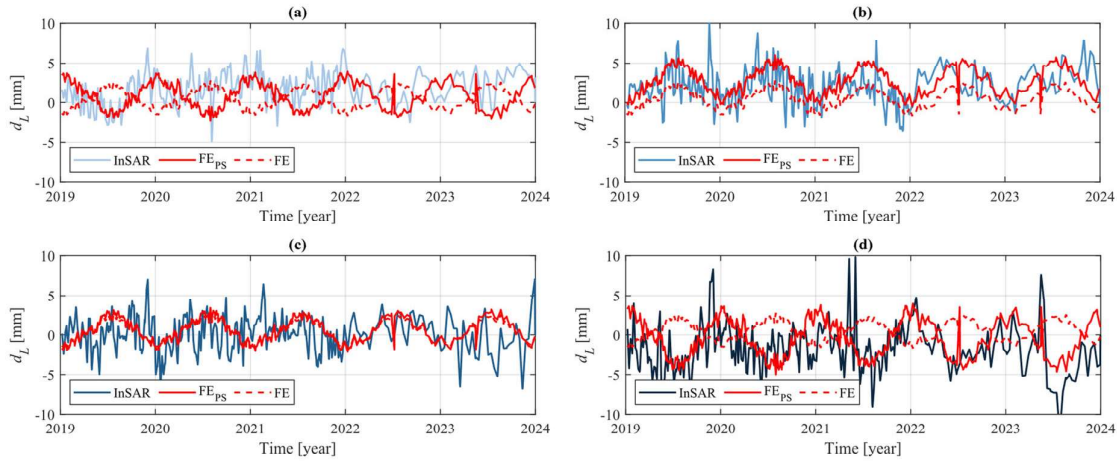


Fig. 5. Longitudinal displacement time series for eastern zones (a) 30E, (b) 32E, (c) 34E, and (d) 36E. For each are compared InSAR-derived displacements (blue), FE predictions at the PS centroid (solid red), and FE predictions of the geometric centroid (dashed red).

4. Conclusions

This study addressed the interpretation of InSAR-derived displacements for the A21 Po River Bridge through comparison with the response predicted by a calibrated FE model. The satellite-derived time histories indicate a predominantly thermally driven response, characterized by larger and more regular longitudinal oscillations in the western portions of the main spans and in the suspended spans, and by a more limited response in the eastern portions. The FE model, initially calibrated on a representative Gerber module using experimentally identified modal frequencies and subsequently extended to the investigated deck segment, reproduces these patterns under thermal loading, supporting the structural interpretation inferred from the InSAR observations. The overall agreement between measured and simulated responses also highlights the potential of InSAR as a reliable tool for capturing the structural behaviour of bridges under operational conditions. The reconstruction of displacement components from InSAR data relies on simplifying assumptions, including the neglect of transverse motion. In the present case, this assumption does not appear to introduce significant bias in the interpretation of the longitudinal response, as supported by the agreement with the FE results, although further investigation is required to assess its general validity. The comparison between measured and predicted displacements also shows that, in proximity of the cylindrical hinges, the results are highly sensitive to the spatial reference adopted for FE displacement extraction. In particular, referring the numerical results to the centroid of the PSs, rather than to the geometric centroid of the analysis zones, improves the consistency of the comparison with the satellite measurements.

Despite these results, some limitations should be acknowledged. In particular, the discrepancy observed for the fundamental mode suggests that additional refinement of the model is required to better capture the global dynamic behaviour. Future work will focus on the development of automated calibration procedures for support devices, aimed at identifying spatial variability in their mechanical properties along the bridge. In particular, the calibration of support stiffness parameters based on monitoring data may enable the detection of differences between spans, potentially associated with degradation mechanisms such as corrosion. This direction is expected to enhance the interpretability of InSAR-derived displacements and to support condition assessment at the level of individual structural components.

Acknowledgments

The authors gratefully acknowledge the support of the RELUIS Project WP 6 – MONITORAGGIO E DATI SATELLITARI – Prog. 2024-26, Task 6.3 “Protocolli per l’integrazione di dati on-site e satellitari”.

References

- An, Y., Chatzi, E., Sim, S., Laflamme, S., Blachowski, B., & Ou, J. (2019). Recent progress and future trends on damage identification methods for bridge structures. *Structural Control and Health Monitoring*, 26(10). <https://doi.org/10.1002/stc.2416>
- Baraccani, S., Palermo, M., Azzara, R. M., Gasparini, G., Silvestri, S., & Trombetti, T. (2017). Structural Interpretation of Data from Static and Dynamic Structural Health Monitoring of Monumental Buildings. *Key Engineering Materials*, 747, 431–439. <https://doi.org/10.4028/www.scientific.net/KEM.747.431>
- Crosetto, M., Monserrat, O., Cuevas-González, M., Devanthéry, N., & Crippa, B. (2016). Persistent Scatterer Interferometry: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 115, 78–89. <https://doi.org/10.1016/j.isprsjprs.2015.10.011>
- Crosetto, M., Solari, L., Balasis-Levinsen, J., Bateson, L., Casagli, N., Commerci, V., Frei, M., Guerrieri, L., Mroz, M., Moldestad, D. A., Oyen, A., & Andersen, H. S. (2022). Ground Motion Examples from the European Ground Motion Service. *IGARSS 2022 - 2022 IEEE International Geoscience and Remote Sensing Symposium*, 5109–5112. <https://doi.org/10.1109/IGARSS46834.2022.9884088>
- Fritzen, C. P. (2005). Vibration-Based Structural Health Monitoring – Concepts and Applications. *Key Engineering Materials*, 293–294, 3–20. <https://doi.org/10.4028/www.scientific.net/KEM.293-294.3>
- Giordano, P. F., Kamariotis, A., Giardina, G., Chatzi, E., & Limongelli, M. P. (2025). Uncertainty propagation in satellite InSAR data analysis for structural health monitoring. *Automation in Construction*, 177, 106371. <https://doi.org/10.1016/j.autcon.2025.106371>
- Giordano, P. F., Kwapisz, M., Miano, A., Liuzzo, R., Vorwagner, A., Limongelli, M. P., Prota, A., & Ralbovsky, M. (2025). Monitoring of a multi-span prestressed concrete bridge using satellite interferometric data and comparison with on-site sensor results. *Structural Concrete*. <https://doi.org/10.1002/suco.202400881>
- HO TONG MINH, D., Hanssen, R., & Rocca, F. (2020). Radar Interferometry: 20 Years of Development in Time Series Techniques and Future Perspectives. *Remote Sensing*, 12(9), 1364. <https://doi.org/10.3390/rs12091364>
- Hrysiewicz, A., Khoshlahjeh Azar, M., & Holohan, E. P. (2024). EGMS-toolkit: a set of Python scripts for improved access to datasets from the European Ground Motion Service. *Earth Science Informatics*, 17(4), 3825–3837. <https://doi.org/10.1007/s12145-024-01356-w>
- Hsieh, K. H., Halling, M. W., & Barr, P. J. (2006). Overview of Vibrational Structural Health Monitoring with Representative Case Studies. *Journal of Bridge Engineering*, 11(6), 707–715. [https://doi.org/10.1061/\(ASCE\)1084-0702\(2006\)11:6\(707\)](https://doi.org/10.1061/(ASCE)1084-0702(2006)11:6(707))
- Ivanov, N. (2026). Assessment of Structural Health Monitoring Systems for Bridges. *International Journal of Hydropower and Civil Engineering*, 7(1), 05–07. <https://doi.org/10.22271/27078302.2026.v7.i1a.76>
- Karakostas, C., Quaranta, G., Chatzi, E., Zulfikar, A. C., Çetindemir, O., De Roeck, G., Döhler, M., Limongelli, M. P., Lombaert, G., Apaydin, N. M., Pakrashi, V., Papadimitriou, C., & Yeşilyurt, A. (2024). Seismic assessment of bridges through structural health monitoring: a state-of-the-art review. *Bulletin of Earthquake Engineering*, 22(3), 1309–1357. <https://doi.org/10.1007/s10518-023-01819-3>
- Laanata, F., & Grosso, A. Del. (2006). Damage detection and localization for continuous static monitoring of structures using a proper orthogonal decomposition of signals. *Smart Materials and Structures*, 15(6), 1811–1829. <https://doi.org/10.1088/0964-1726/15/6/036>
- Liuzzo, R., Giordano, P. F., & Limongelli, M. P. (2025). *Quantifying uncertainty in InSAR-derived displacement measurements for bridge monitoring*. 13. <https://doi.org/10.1117/12.3050715>
- Morleo, E., Limongelli, M. P., Piscini, A., & Troielli, E. (2025). *A Transfer Learning approach for damage identification in operational viaducts*. <https://doi.org/10.3217/978-3-99161-057-1-136>
- Raventós, J., Couso, C., & Garcia, J. (2017). *The use of InSAR technology to monitor ground and structural displacements*. <https://api.semanticscholar.org/CorpusID:209006359>
- Yang, X., Zhou, Y., Li, X., & Zhang, J. (2024). Effect of temperature changes on bearing motion of long-span steel truss continuous girder bridge. *Construction and Building Materials*, 430, 136440. <https://doi.org/10.1016/j.conbuildmat.2024.136440>