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DOI
10.1016/j.prostr.2024.09.063

Publication date
2024

Document Version
Final published version

Published in
Procedia Structural Integrity

Citation (APA)
Farneti, E., Cavalagli, N., Giardina, G., Macchiarulo, V., Milillo, P., & Ubertini, F. (2024). Structural Health Monitoring of Typical Urban Bridges in the Netherlands Combining Collapse Simulations and Monitoring Data. *Procedia Structural Integrity*, *62*, 438-445. https://doi.org/10.1016/j.prostr.2024.09.063

Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 62 (2024) 438–445

Structural Integrity
Procedia

www.elsevier.com/locate/procedia

II Fabre Conference – Existing bridges, viaducts and tunnels: research, innovation and applications (FABRE24)

Structural Health Monitoring of Typical Urban Bridges in the Netherlands Combining Collapse Simulations and Monitoring Data

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Abstract

Bridges play a vital role in the European transport network, and their preservation is of utmost importance. Despite many centuries-old bridges still being in use in European cities, their structural integrity may be compromised due to factors like material degradation, increased traffic loads, extreme events, or slow deformation phenomena. It is essential to regularly assess the current conditions of these structures and monitor their evolution over time to enable timely intervention when necessary. This study presents the first results of a multidisciplinary methodology for the Structural Health Monitoring (SHM) of typical urban bridges in the Netherlands, combining numerical simulations using the Applied Element Method (AEM) with monitoring data derived from various sensing sources. These sources range from standard in situ techniques to satellite remote sensing using Synthetic Aperture Radar Interferometry (InSAR). The methodology is applied to a representative bridge of Amsterdam canals. The nonlinear analyses have led to a numerically predicted crack pattern consistent with on-site observations. The simulated damage progression until collapse identifies critical points of the bridge to be kept under control with monitoring activities.

Keywords: Structural health monitoring, Bridges, Remote sensing, SAR Interferometry, Progressive collapse analysis, Applied element method.

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10.1016/j.prostr.2024.09.063

1. Introduction

Bridges represent an essential part of the European transport network, whose preservation holds a primary importance. Many bridges built in past centuries are still in service in European cities, even though their structural performance might be deficient due to material degradation, increase of traffic loads, extreme events or slow deformation phenomena. It is essential to regularly assess the current conditions of these assets and monitor their evolution over time to enable prompt intervention when needed. In this framework, Structural Health Monitoring (SHM) practices guarantee a systematic collection of data, and a multidisciplinary approach is to be preferred to cross-reference information from heterogeneous sources (Laflamme et al., 2023; García-Macías et al, 2023).

Recent bridge monitoring strategies, among several approaches, involve the use of satellite remote sensing technique, specifically employing Synthetic Aperture Radar (SAR) interferometry (Macchiarulo et al., 2021; Giordano et al., 2022; Macchiarulo et al., 2022; Farneti et al., 2023a; Nettis et al., 2023). Processing SAR images acquired by satellites enable to track the temporal evolution of slow movements of a structure through the observation of specific points of opportunity characterized by a stable electromagnetic signature (Persistent Scatterer, PSs). PSs measure movement along the satellite Line-Of-Sight (LOS) direction connecting the satellite radar antenna to the target on Earth. Using SAR acquisitions from both ascending and descending geometries, only two components of the three-dimensional displacement vector can be estimated, still adding to this technique a certain level of uncertainty and indeterminacy. The combination of PS with in-situ measurements and visual inspections is, in some cases, fundamental for achieving a reliable diagnosis regarding the health state of a structure.

In this work the first results of a Structural Health Monitoring strategy applied to typical urban bridges in the Netherlands are presented. The proposed approach combines numerical collapse simulations using the Applied Element Method (AEM) and monitoring data from different sensing sources, ranging from standard in-situ techniques to satellite remote sensing with Synthetic Aperture Radar Interferometry (InSAR) (Farneti et al., 2023b). The function of the numerical model is to represent the existing damage situation, to provide an interpretation of the structural condition, and to simulate the most critical scenarios that could arise with the progression of the current damage state. To this aim, the Applied Element Method, a relatively recent approach known for accurately reproducing both continuous and discrete behaviours of structures, is able to describe various stages of structural collapse, including elastic deformation, crack initiation, steel yielding, element separation, and ultimately collapse. In the AEM model, the structure is described by 3D elements, connected by normal and shear springs at the interfaces representing the material properties. The literature provides several examples of AEM's application to simulate collapse mechanisms in different structural systems, including bridges (Garofano and Lestuzzi, 2016; Scattarreggia et al., 2022).

In this paper, the methodology has been applied to a bridge example representing typical structures that span the Amsterdam canals. The results of the collapse analyses have facilitated the investigation of various mechanisms related to foundation failures, yielding a numerically predicted crack pattern compatible with the those observed on site.

2. The case study among Amsterdam urban bridges

The city of Amsterdam is characterized by the presence of many urban bridges, facilitating the passage over the canals that branch out along the city. Several of these bridges were built in past centuries and their current conditions make them in need of special attention. The study focused in particular on a bridge used by motor vehicles, cyclists and pedestrians, named Paulusbroedersluis (Bridge 215), consisting of one span, with a steel-reinforced concrete deck over masonry abutments and wooden pile foundation. Bridge 215 (Fig. 1a) is located in the Oude Hoogstraat over the Oudezijds Achterburgwal and was built around 1745. The bridge deck was first widened and lowered in 1869 and then replaced in 1966, while retaining the original substructure.

The main load-bearing structure of the bridge is composed by longitudinal steel girders with a reinforced concrete deck having dimensions of about 7 m in length and about 5 m in width. After the widening of the deck in 1869 and its replacement in 1966 (Fig. 1b), the deck counts eighteen steel girders. The abutments are made of masonry, up to 1 m below the waterline. The thickness of the quay walls and the abutments, estimated from in-situ drilling cores, is equal to 1 m and 2.5 m, respectively. The foundations of the abutments are composed by wooden floor and piles, characterized by several dimensions in diameter (between 180 and 280 mm), on which the masonry stands on.

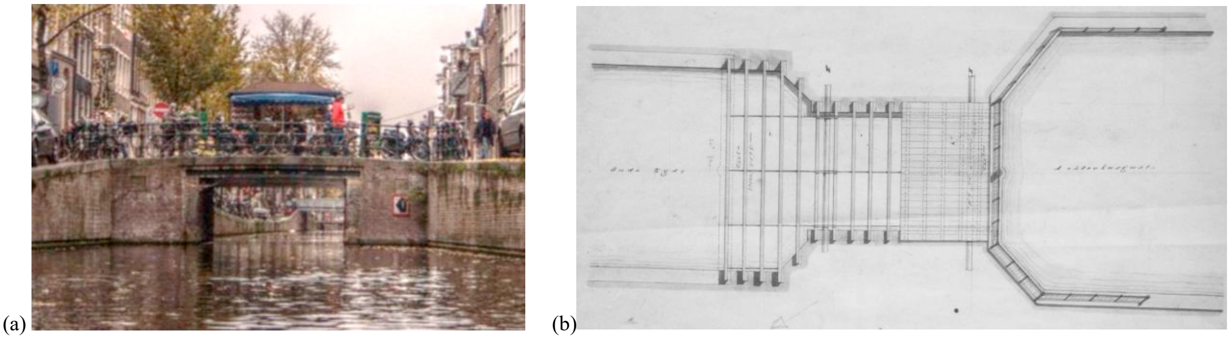

Fig. 1. Amsterdam bridge under study: Bridge 215. (a) Photographic image. (b) Original design tables of deck widening made in 1869.

Fig. 2. Diagonal cracks in the West (a) and East (b) wing walls. Vertical (c) and horizontal (d,e) cracks on the East abutment.

In the last years Bridge 215 has been subject to on-site inspections. A first technical inspection was executed in 2016, to determine its health condition. Even if no safety risks were identified for the asset, structural diagonal cracks approximately 0.1-0.5 mm wide were detected in the wing walls (Figg. 2a-2b). The report of another visual inspection carried out in 2020 declared that the width of the diagonal cracks had reached 2 mm, and highlighted the presence of vertical and horizontal cracks on the East abutment, characterized by a maximum width of 1 mm and 5 mm, respectively (Figg. 2c-2e). Based on the evidence of the same inspection and on wood samples analysis, it was also concluded that the condition of the wooden pile foundation of the bridge was very poor due to the action of erosion bacteria. In particular, at the height of the pile head, 83% of the tested piles had insufficient capacity, while, at the height of the critical cross-section, all piles had insufficient capacity. After further investigation on the foundation, the municipality decided to strengthen the bridge with an emergency construction.

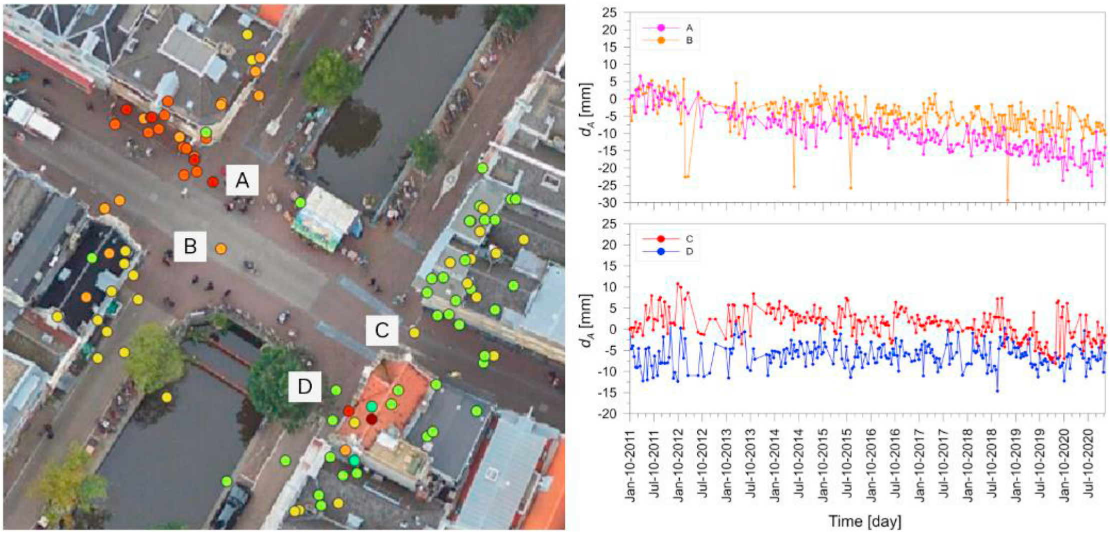

Fig. 3. LOS deformation of PSs detected in the proximity of the abutments of Bridge 215 in ascending geometry.

3. Structural monitoring by remote sensing and in-situ measurements

The structural monitoring activities of Bridge 215 have been conducted by using both remote sensing and in-situ standard techniques. TerraSAR-X InSAR data processed and provided by SkyGeo (Venmans et al., 2020) have been used for the satellite-based monitoring of the area of interest. Two stacks of images, recorded in ascending and descending geometries, were available. The ascending dataset consisted of 246 images taken between January 2011 and November 2020, while the descending dataset consisted of 145 images taken between March 2016 and December 2020. As an example, the maps shown in Figure 3 include all PSs obtained by the ascending geometry, located within a buffer of 20 m from the centroid of each bridge. The figures show that few PSs are available above the bridge deck, due to the reduced length of the assets and the possible shadowing effect caused by the presence of buildings.

It is evident that the PSs detected in the vicinity of the abutments have been affected by movements away from the satellite sensor (of a negative sign by convention) during the observation period, for both viewing geometries. This suggests that the main component of the real motion has occurred in a downward vertical direction. In particular, when examining the time series trend of the PSs within the influence area of abutments, one can observe an accumulation of irreversible deformations on the order of centimetres along the LOS direction for both ascending and descending configurations.

An in-situ displacement measurement campaign for movements in longitudinal, transverse and vertical direction was recently carried out using a total station, to determine possible relative deformations affecting the bridge. The structure was monitored during the two-year period from 2020 to 2022, using brass bolt and measurement reflectors to ensure the relative movements between points located on the top of the bridge and of the abutment walls. In Figure 4, as an example, only the displacement time histories of the points located on the South side of West and East abutments are reported, with the points on the North side experiencing similar trends.

The results of the deformation analysis highlighted the occurrence of settlements affecting the bridge during the monitored period, as evidenced by the trend of vertical displacement of some points on the bridge deck and abutments, even if the values in the period are relatively small. In fact, the downward vertical displacement remains below 2 mm for almost all measurement points. Nevertheless, the damage scenario detected by visual inspections confirmed significant deformations occurred in the past, requiring continued monitoring activities.

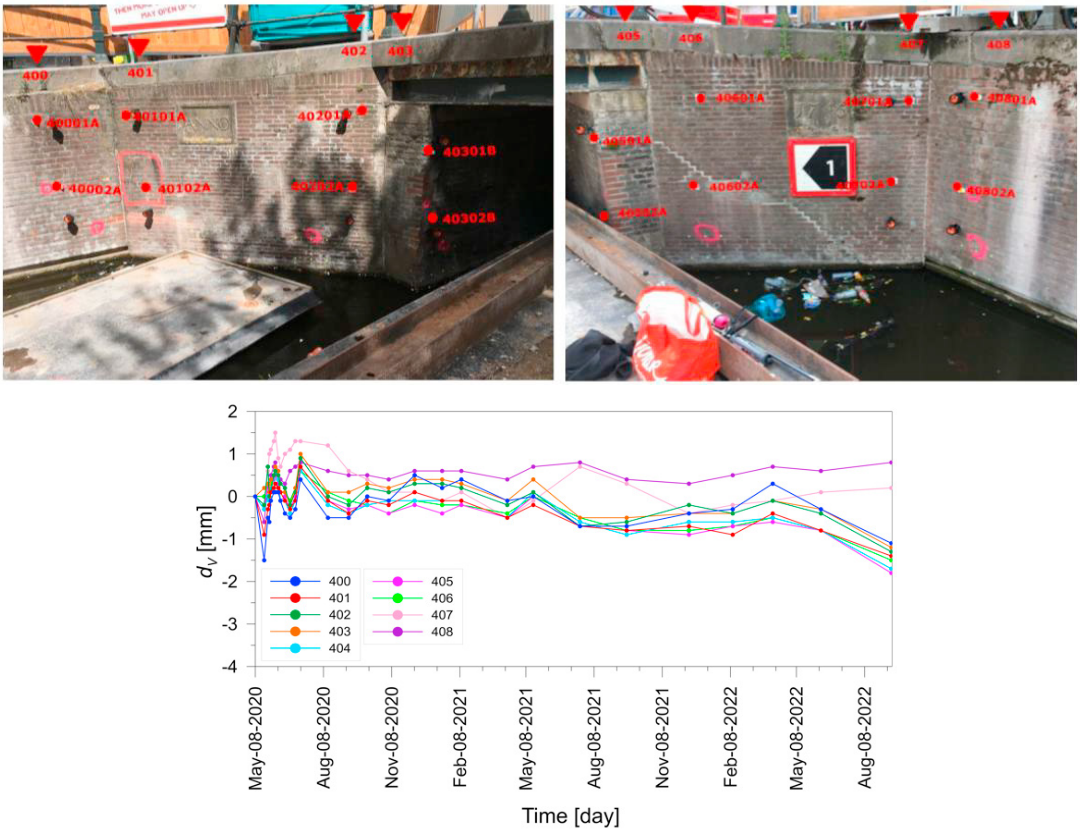

Fig. 4. Vertical displacements of in-situ measurement points on Bridge 215. Positive values indicate upward movements.

4. Interpretation of the crack pattern through nonlinear numerical analysis

4.1. Applied Element Method modelling

Due to the typological nature of the investigation, where urban bridges in the municipality of Amsterdam share similar geometrical properties and structural issues, it has been chosen to build a single numerical model. This model aims to serve as a representative prototype, which could yield generalizable results applicable to this bridge typology. Therefore, the model's objective is not to precisely reproduce the peculiarities of Bridge 215, but rather to capture its main features and simulate its behaviour with a sufficiently level of accuracy.

The Applied Element model (Fig. 4) includes the deck, whose geometry corresponds to a generic bridge. The parameters for this model have been extracted from a typological analysis: the abutments are 3.7 m high and 1.4 m thick, a portion of quay walls is 1 m thick and extended for 4 m on both sides, the soil behind the walls has been modelled up to 5.4 m from the abutments walls, the foundation floor has a thickness of 20 cm, while the heads of the foundation piles a diameter of 210 mm and arranged on a regular grid of 1 x 1 m^2. The choice to model only the heads of the piles is due to the absence of information on their total length and on the characteristics of the soil in which they are embedded. The soil-foundation interaction has therefore been taken into account indirectly, through fixed constraints applied on the pile heads. Roller constraints have been assigned to the elements belonging to the lateral surfaces that delimit the outwards extension of walls and soil. The deck, the soil and the foundation have been discretized using 8-node elements, while the abutments and quay walls have been modelled employing 6-points prisms, to allow the propagation of the cracks (only possible along the edges of the elements) in any direction. Overall, the model consists of approximately 91,000 solid elements.

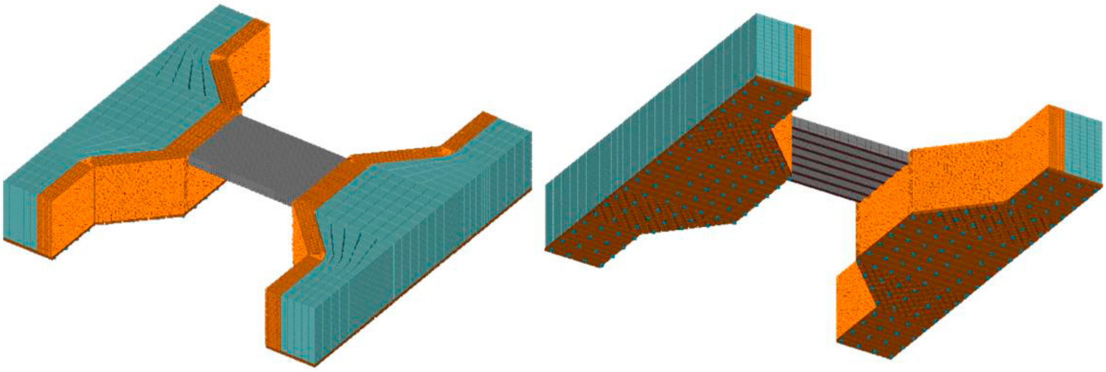

Fig. 5. Geometry and mesh discretization of the AEM model reproducing the generic bridge crossing Amsterdam's canals.

Table 1. Material properties adopted for the numerical model. E and G are the Young and shear moduli, respectively; f_c and f_t are the compressive and tensile strength, respectively, while τ_0 is the shear strength; σ_y and σ_u are the yield and ultimate stress, respectively. All the values are expressed in MPa.

Structural element type	E	G	f_c	f_t	τ_0	σ_y	σ_u
Concrete	26200	10480	29.4	2.94	7.35	-	-
Steel reinforcing bars	200000	80000	-	-	-	353	494
Steel beams	210000	80000	-	-	-	235	360
Masonry	5000	2000	8.5	0.3	1	-	-
Soil	78.5	30.2	19613.3	-	-	-	-
Wooden foundation floor	11768	7845.3	29.4	2	0.2	-	-

Masonry material has been modelled through a homogenization approach, i.e. condensing the equivalent mechanical properties on the interface springs which connect the elements. The material densities have been set equal to 1800 kg/m^3 for the masonry, 2000 kg/m^3 for the soil, 2500 kg/m^3 for the concrete, 7840 kg/m^3 for the steel of beams and reinforcements, and 700 kg/m^3 for the wood. The Maekawa constitutive model (Maekawa and Okamura, 1983) has been employed to describe the behaviour of masonry and concrete, while the Menegotto-Pinto relationship (Menegotto and Pinto, 1973) has been used to model the steel. The soil has been represented through a bearing model. For the wood a model developed and validated within the work of Eng. Filippo Grande and Eng. Marianna Sabia of the VORM4 Company during the assessment of existing buildings subjected to induced earthquakes in the Groningen region (The Netherlands) has been implemented. The model applies the Mohr-Coulomb failure criteria and includes the fracture energy in tension and in compression. A bearing model has been assigned to the springs at the interface between the soil and the parts of the structure in contact with it, to avoid the propagation of tensile stresses, and at the interface between the foundation and the masonry, to ensure that the walls are not dragged down due to a connection with the floor during the settlement simulation. Finally, the bearing model used for the interface springs between the deck and the masonry has been necessary to reproduce the support constraint. The values of the main parameters assumed for characterizing the constitutive models are summarized in Table 1.

4.2. Nonlinear numerical simulations

The numerical collapse analysis aims to comprehend the nature of the deformation phenomena behind the formation of the crack pattern observed on site for the examined structure, and to predict the evolution of the damage. The proposed methodology under development aims to assess the current state of the bridge and, through numerical simulations, to estimate its distance from a critical condition.

InSAR monitoring and the knowledge acquisition phase have highlighted that the abutments and quay walls of the bridge are affected by differential vertical displacements, which are hypothesized to be related to the formation of the crack patterns. One of the potential causes of these settlements has been assumed to the ongoing degradation of the wooden foundation and, as a consequence, to the loss of stiffness and capacity of them. The input of the nonlinear numerical simulation has therefore been defined consistently with this hypothesis, with the intention of reproducing a loss of foundation vertical restraints, and then investigating the consequences on the above structure. Such an input consists of progressive predefined vertical settlements applied to the top section of some piles.

Several scenarios have been considered, where the vertical displacements involve alternatively different group of piles, with a symmetric or asymmetric configuration with respect to the axis of symmetry of the abutment. In the following, the results obtained by the scenario characterized by three rows of piles in front of the abutment are shown. It has also been assumed that the displacements are consistent with a rotation movement whose centre lies on the row of piles closest to the last one involved in the mechanism. The numerical analysis has been carried out by subjecting the model to two loading steps: the first one is static and only self-weight with fixed foundation is applied; the second is quasi-static with the application of settlement schemes at the base. The maximum displacement imposed, applied to the outermost row of piles (symmetric configurations) or to the pile at the corner between the front and lateral wall (asymmetric configurations), has been set equal to 150 mm.

The maximum principal strain contour shown in Figure 6, which allows visualizing the distribution of cracks predicted by the simulations corresponding to 10 mm of vertical displacement imposed, is compatible with the crack pattern observed on the structure (Fig. 2). In particular, even for low values of the applied displacements, the formation of diagonal and horizontal cracks is evident on the abutment affected by the settlement imposed. The progression of the analysis has given the opportunity to follow the evolution of damage, which, as shown in Figure 7, has led to the definition and detachment of a masonry wedge, similar for all the considered scenarios, and typical shear damages.

As explained in the previous sections, the results of these advanced simulations will be used in the proposed methodology to estimate critical conditions of the structure combining monitoring data and displacement time histories extracted by the numerical models.

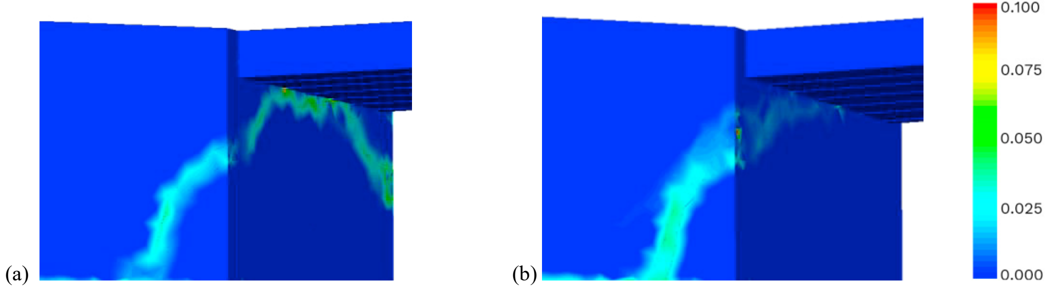

Fig. 6. Principal tensile strains of the analysed scenario for a max vertical displacement equal to 10 mm: symmetric (a) and asymmetric (b) configuration.

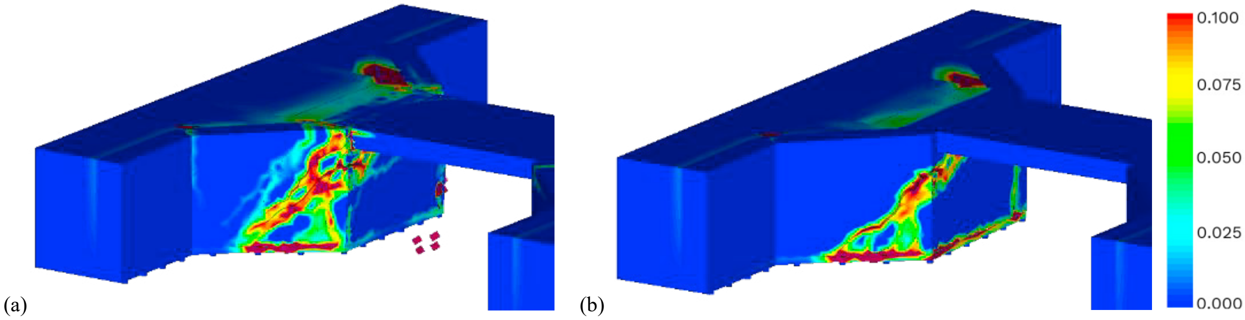

Fig. 7. Principal tensile strains of the analysed scenario for a max vertical displacement equal to 150 mm: symmetric (a) and asymmetric (b) configuration.

4. Conclusions

This paper presents the first results of a multidisciplinary methodology for the structural health monitoring of typical urban bridges in Amsterdam. The method is based on the combination of monitoring data and non-linear numerical simulations, which are able to predict critical conditions up to the collapse. The methodology has been applied to a real case study, Bridge 215 over one of the Amsterdam canals. The bridge is characterized by a single span deck fixed on to abutments made on masonry material, which stand on wooden deep foundations.

Structural monitoring activities, including remote sensing and standard techniques based on in-situ measurements, have been carried out to improve the knowledge of the current condition. This is particularly crucial due to data limitation, i.e. in terms of spatial density for InSAR data and temporal evolution for in-situ measurements. This effort aimed to achieve a better understanding of the ongoing structural deformations affecting the abutments. Nonlinear numerical simulations using the Applied Element Method allowed to reproduce the current damage scenario and to predict its evolution. In a subsequent phase of this research, the combination of monitoring data and structural collapse simulations will enable the prediction of potential critical conditions.

Acknowledgements

This publication is part of the Vidi project InStruct, project number 18912, financed by the Dutch Research Council (NWO). The work was also supported by the Italian Ministry of Education, University and Research (MIUR) through the funded project of national interest "FAIL-SAFE: near-real-time perFormance Assessment of exIsting buiLdings Subjected to initiAl Failure through multi-scalE simulation and structural health monitoring" (Protocol No. 2022JFXE95).The authors gratefully acknowledge SkyGeo Netherlands B.V. for providing InSAR data, and the City of Amsterdam for the in situ monitoring data.

References

Farneti, E., Cavalagli, N., Costantini, M., Trillo, F., Minati, F., Venanzi, I., Ubertini, F., 2023a. A method for structural monitoring of multispan bridges using satellite InSAR data with uncertainty quantification and its pre-collapse application to the Albiano-Magra Bridge in Italy. Structural Health Monitoring 22(1), 353–371.

Farneti, E., Cavalagli, N., Venanzi, I., Salvatore, W., Ubertini, F., 2023b. Residual service life prediction for bridges undergoing slow landslide-induced movements combining satellite radar interferometry and numerical collapse simulation. Engineering Structures 293, 116628.

García-Macías, E., Ruccolo, A., Zanini, M.A., Pellegrino, C., Gentile, C., Ubertini, F., Mannella, P., 2023. P3P: a software suite for autonomous SHM of bridge networks. Journal of Civil Structural Health Monitoring 13(8), 1577–1594.

Garofano, A., Lestuzzi, P., 2016. Seismic Assessment of a Historical Masonry Building in Switzerland: The "Ancien Hôpital De Sion.". Int J Archit Herit 10, 975–92.

Laflamme, S., Ubertini, F., Di Matteo, A., Pirrotta, A., Perry, M., Fu, Y., Li, J., Wang, H., Hoang, T., Glisic, B., Bond, L.J., Pereira, M., Shu, Y., Loh, K., Wang, Y., Ding, S., Wang, X., Yu, X., Han, B., Goldfield, Y., Ryu, D., Napolitano, R., Moreu, F., Giardina, G., Milillo, P. Roadmap on measurement technologies for next generation structural health monitoring systems. Measurement Science and Technology 34(9), 093001.

Macchiarulo, V., Milillo, P., Blenkinsopp, C., Giardina, G., 2022. Monitoring deformations of infrastructure networks: A fully automated GIS integration and analysis of InSAR time-series, Structural Health Monitoring 21(4), 1849–1878.

Macchiarulo, V., Milillo, P., Blenkinsopp, C., Reale, C., Giardina, G., 2021. Multi-temporal InSAR for transport infrastructure monitoring: recent trends and challenges. Proceedings of the Institution of Civil Engineers - Bridge Engineering 176(2), 92–117.

Maekawa, K., Okamura, H., 1983. Deformational Behavior and Constitutive Equation of Concrete Using the Elasto-Plastic and Fracture Model. J Fac Eng Univ Tokyo, Ser B; 37, 253–328.

Menegotto, M., Pinto, P.E., 1973. Method of Analysis for Cyclically Loaded R. C. Plane Frames Including Changes in Geometry and Non-Elastic Behavior of Elements under Combined Normal Force and Bending. Proc IABSE Symp Resist Ultim Deform Struct Acted by Well Defin Loads, 15–22.

Nettis, A., Massimi, V., Nutricato, R., Nitti, D.O., Samarelli, S., Uva, G., 2023. Satellite-based interferometry for monitoring structural deformations of bridge portfolios. Automation in Construction 147,104707.

Giordano, P.F., Turksezer, Z.I., Previtali, M., Limongelli, M.P., 2022. Damage detection on a historic iron bridge using satellite DInSAR data. Structural Health Monitoring 21(5), 2291–2311.

Scattarreggia, N., Salomone, R., Moratti, M., Malomo, D., Pinho, R., Calvi, G.M., 2022. Collapse analysis of the multi-span reinforced concrete arch bridge of Caprigliola, Italy. Engineering Structures, Part A 251, art. no. 113375.

Venmans, A.A., Op De Kelder, M., De Jong, J., Korff, M., Houtepen, M., 2020. Reliability of InSAR satellite monitoring of buildings near inner city quay walls. Proceedings of the International Association of Hydrological Sciences 382, 195-199.