

REVIEW OF STRUCTURAL HEALTH MONITORING METHODS FOR THE ASSESSMENT OF PROBABILISTIC MODELS OF IMPOSED LOADS

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Keywords: Structural Health Monitoring, SHM, load models, imposed load.

Abstract. Probabilistic models of imposed loads require adjustments to reflect current knowledge and experience. To do so, relevant data about their spatial and temporal variability must be collected. Structural Health Monitoring allows to estimate loads acting on bridges by measuring the relevant strains or deflections. Adapting this approach to buildings is not straightforward due to the increased complexity of such systems. This study reviews existing methods and past experiments carried out for buildings and assesses their relevance for estimating the magnitude, position, and duration of loads, establishing a foundation for future laboratory and in-situ tests.

1 INTRODUCTION

Climate change has increased awareness and created a higher demand for sustainable and, thereby, efficient and environmentally friendly structures designed to optimise material utilisation. Meeting these demands requires improved design methods and better modelling of load and resistance uncertainties. Their description entails the definition of probabilistic models, i.e., probability distributions, which may require adjustments over time to reflect current knowledge and experience.

Imposed loads on building slabs (due, for example, to people, furniture, and equipment) exhibit spatial and temporal variability. To identify the magnitude and distribution of loads for different categories of use (residences, offices, retail, etc.), load surveys for imposed loads were conducted in the past [1–3]. Old methods often used manual labour, were invasive and time-consuming. Technical personnel visited buildings in person, counted the number of people, weighed furniture, and documented information about loads. Similar estimations can be made based on photographic documentation, although the quality of the data that can be derived is

lower.

Another idea pursued in the past is a Delphi survey [4], which involved collecting responses to questionnaires from different offices about furniture, personnel, and estimated loads. This provided access to data collected from more sources, as it was non-invasive and time-efficient. However, results were uncertain and affected by human error as they were based on estimations carried out by untrained persons.

Recent technological developments have brought more advanced tools for load assessment. Cameras with AI systems trained for image segmentation and object recognition (YOLO) have made a breakthrough in load surveying and capturing temporal variability [5]. This system enables the continuous and dynamic estimation of imposed loads, tracks the weights of furniture and equipment, and follows the movement of people. Privacy regulations and issues related to people's comfort might pose a challenge, especially in non-public places (working spaces, residential properties). To tackle this issue, the use of pictures of interiors available online has been proposed [6]. However, this approach does not allow to account for load variability over time. Another limitation is that it only measures visible objects, so the weights of hidden items must be estimated statistically.

As none of the methods used in the past can capture temporal variability, one of the problems with probabilistic load models is the high uncertainty of intermittent loads (from gatherings, evacuations, and furniture stacking). With continuous or nearly continuous readings, there is a chance to capture such behaviour, and increase our knowledge on the most uncertain and, at the same time, most critical imposed loads. Measurement of loads has been attempted using force platforms (large, self-constructed scale) [7] or piezoresistive sensors. Force platforms are used mainly for dynamic load estimation and are of little significance for the study of static loads. Piezoresistive sensors just started to gain attention for wind or snow monitoring [8] although only one laboratory study has been found by the authors at the time of writing. Indirect monitoring of loads through deflections or strains measured on slabs, successfully implemented in bridge weight-in-motion systems, is not widely implemented in buildings. One reason for this is that bridges have a beam-like behaviour and loads are significant which makes it easier to capture them through deflection measurements. Loads on building slabs are relatively small, slabs have a bi-dimensional behaviour with relatively high stiffness, and boundary conditions are uncertain. This leads to small displacements and strain values which, together with material irregularities and environmental changes, makes it complicated to precisely measure the loads on the slabs.

This study reviews existing methods and past experiments to evaluate the idea of using SHM for indirect load assessment through deflection or strain monitoring. The aim is to establish a foundation for future laboratory and in-situ techniques that can further enhance knowledge of the magnitude, position, and time variability of imposed loads. This will allow to update the probabilistic load models currently available in the literature to better reflect actual applied loads, reducing uncertainties in design and, in turn, leading to optimised structural solutions.

2 SCOPING STUDY ON SHM USE

The understanding of loads spatial and temporal variability and the creation of consistent load models, through the measurement of their effects (e.g. deflections, strains) requires answering to several questions:

- Can we capture the load effect and identify its source (load, moisture, creep, etc.)?
- Can we evaluate the load from the load effect?
- Can we measure the spatial variability of the load effect?
- Can we measure the temporal variability of the load effect?

A short scoping study was conducted to answer these questions. It consists of three stages for selecting the most relevant articles: searching, screening, and reading.

The first stage involves conducting various searches in two scientific databases, Scopus and Web of Science, to identify all relevant articles. Specific packages of synonyms were used:

- **Load** ("vertical load*" OR "impos* load*" OR "live load*")
- **Slab** ("slab*" OR "plate*" OR "floor*")
- **Strain** ("strain" OR "stress*" OR "deform*" OR "deflect*")
- **Test** ("test*" OR "method*" OR "measur*" OR "procedur*")

Moreover, for each search, the word “bridge” was excluded from abstract and keywords, along with limiting disciplines to engineering. The language was limited to English, and an additional requirement of the word “load” in the title was added to capture articles focusing on loads and load effects. **Table 1** presents the results of those searches.

Table 1. Search results, search taken into the next phase marked in bold

Searched words		Number of articles found	
		Scopus	Web Of Science
1	Strain AND slab AND test	2 676	1 644
2	Load AND slab	206	110
3	Load AND slab AND test	157	76
4	Load AND strain AND slab AND test	69	32

The scope of this study includes research on the use of SHM techniques to monitor the load on slabs. For this reason all articles from the third search in Scopus and Web of Science were deemed relevant to be subject to more detailed scrutiny (i.e., screening). During the screening process, it was assessed whether the article focused on the use of SHM to directly estimate the load on the slab. Studies performing deflection or strain controls of existing structures for, e.g., early warning systems, were also included in the selected literature, as well as articles including a comparison between field/experimental studies and Finite Element Models (FEMs). Articles focusing on dynamic monitoring were excluded as the results have little significance in the case of static loading. Similarly, articles investigating the use of SHM for damage identification were excluded. A total of 63 articles were selected for further investigation.

The third phase involved selecting articles that broadened the understanding of SHM for load monitoring by comparing models’ outcomes and SHM results and describing methods for obtaining load magnitudes and distributions from SHM measurements. Furthermore, articles reporting interesting conclusions from lab or field studies or pointing out possible obstacles to using SHM for load monitoring were selected.

The 15 most interesting articles are discussed in detail below.

3 RESULTS AND ANALYSIS

The literature study confirmed that using SHM to investigate imposed loads is not common in structural engineering and is conducted almost exclusively in case of dynamic or acoustic problems. However, several studies indicate that SHM holds strong potential for long-term monitoring and effectively capturing load variability (both spatial and temporal).

3.1 Types of sensors

The choice of SHM sensors and techniques must be tailored to the specific needs of the structure, the desired outcomes, and the influence of environmental factors. For this reason, many cases in the literature required a pre-study to determine the optimal measuring system. A comprehensive list of sensors and methods for monitoring timber structures is provided by Helmer-Smith et al. [9], along with their limitations.

In general, measuring methods can be classified as contact-based and non-contact. Among contact-based methods, Linear Variable Displacement Transducers (LVDT) are some of the most widely used: they provide one-dimensional (1D) displacement measurements at specific locations along the elements. They can collect continuous data but are sensitive to environmental factors and require a reference system. Electric strain gauges (ESG) are also well-established, providing strain data in discrete locations; they are relatively inexpensive but are difficult to install correctly and are prone to long-term sensor creep and drift. Recently, Fiber Optic Sensors (FOS) and Fiber Bragg Grating (FBG) sensors have been widely used due to their quasi-distributed measurements of strain and reliability for long-term monitoring. The main disadvantages include large data sets and complex installation. In all cases, effective use of these sensors requires a preliminary study to determine optimal placement, with measurement quality typically improving as the number of sensors increases. Collecting displacement or collecting strain are both valuable alternatives, and, in general, accurate displacements can also be obtained from strain measurements [10].

As an alternative to sensors mounted directly on the structure, vision-based or laser-based systems can also be employed for monitoring. For example, Automatic Total Stations (ATSS) provide the 3D coordinates of target points using a laser-based survey. They don't require contact with the structure and can detect global movements and deformation over large areas. However, they are limited by the line of sight, and only expensive equipment allows for continuous data collection. Similarly, Light Detection and Ranging (LiDAR) offers accurate and distributed deflection and displacement data in a 3D space; however, significant postprocessing and the absence of autonomous operating make it challenging to manage. A general review of this sort of measuring systems [11] points out that a large advantage of vision-based or laser-based systems is quantifying deflection of the whole structure, though those systems might often not be an alternative due to aesthetic reasons.

3.2 From measurement to load

Well-established load–deflection relationships characterise how structures respond to imposed loads. These relationships typically apply within the elastic range before transitioning into plastic behaviour as loads increase. Their existence enables the estimation of imposed loads based on displacement and/or strain measurements obtained from one or more of the sensors

described in Section 3.1. However, any load estimate must be validated, either through detailed analytical models that describe the system's response or through in-situ load measurements.

For example, [12] investigates the relationship between inclinometer measurements (placed on the lower side of a girder) and the snow load on a roof structure. Such a relationship is validated by directly measuring the weight of the snow on the roof using three snow scales strategically placed on it. Measurements are then combined in a Supervisory Control and Data Acquisition (SCADA) system that integrates results with weather conditions and an early warning system.

Another study [13] validates the relationship by comparing different measuring systems for displacements of a prestressed concrete slab in controlled conditions and under load applied in 4 increments. The controlled conditions ensure that the beam behaves according to the analytical mechanical model. The analytically calculated displacements are compared with deflection measurements obtained from several instruments: a total station for 3D point positioning, an accurate level with micrometre for vertical displacements, a rotating laser level with sensors for levelling and large-area displacement measurement, and an inductive meter for precise distance changes. The results show agreement between methods, with the total station performing best and more significant errors for larger deflections.

A study on Canadian timber trusses [14] implements findings from a laboratory study [9]. An ATM is considered the best choice for the conditions and is supplemented with LVDTs (LDS-50), strain gauges, temperature and moisture sensors, a snow scale, and a wind load monitoring system. Trusses are measured at 18 points in vertical, transverse, and longitudinal directions. The study shows that temperature and moisture content changes cause most deformations, demonstrating the importance of monitoring environmental parameters. Results agree with the analytical solution based on standard beam equations and numerical analysis of a digital twin.

A master thesis on a similar topic investigates the behaviour of cross-laminated timber (CLT) slabs under a load applied by a hydraulic actuator and loads in different arrangements [15]. The slab is equipped with two linear potentiometers with spring return, placed in the centre of the span on both sides of the beam and strain gauges glued with adhesive to the bottom of the slab, two in the middle of the span and two in the quarter of the span, to give an understanding about the position of the load. Five tests are conducted: test 1 involves a point load applied at mid-span and is used to calibrate the sensors; test 2 examines various dead load configurations; test 3 investigates loads induced by human activity (walking, jumping); test 4 involves an unknown load condition; test 5 is a run-to-failure test. The study shows good alignment of calibrated results to analytical methods, though there are differences between measurements of different load arrangements.

In general, when estimating loads from displacement or strain measurements, several sources of error can be identified. These include: (1) the ill-posed nature of the inverse problem, where multiple load configurations can produce similar deflection or strain responses; and (2) measurement errors, which result from the inherent imprecision of sensing devices. Studies that approach this problem have offered potential solutions.

A study on simply supported beams [10] utilises strain measurements obtained from seven measured points along the beam. The system is first calibrated with a centrally placed point load. Later, based on measured data, a strain function is determined, regressed, and substituted into a rearranged formula based on beam theory. The study shows that displacements can be

obtained from strain measured with FBG sensors and gauges. Estimated deflection curves coincide well with analytical results, though the applied load is very simple.

An article on aerospace structures [16], using SHM in load measurements as an inverse problem, investigates the potential of Micro-Electro-Mechanical System (MEMS) having LVDT as a reference point. Two platforms under quasi-static point load in the end were tested; the first platform, a rectangular cantilever, was equipped with MEMS in five points along the length (two sensors in line for capturing torsion) and ten LVDT sensors in the same locations. The second platform, a rectangular cantilever with stiffening ribbing, was equipped with fifteen MEMS, ten LVDT sensors and linear strain gauges. The procedure begins with MEMS capturing angles; later, a polynomial fitting to those angles and deflection is performed. The load is then estimated based on a double derivative of these functions and compared to FEM or analytical results. The study shows that estimating loads based on the deflection is possible with well-defined boundary conditions and multiple measuring systems. However, some information is inevitably lost in the process, particularly when dealing with complex or overlapping load combinations, which makes the inverse problem more challenging. The authors, however, see the potential in using machine learning to solve these issues, as such methods are capable of capturing complex, non-linear patterns and relationships that may not be readily apparent through traditional analytical approaches.

The 3D measurements from Monitoring stations can help with the analyses of more complex structures, such as large suspension roofs. A study from Poland [17] focuses on an inverse analysis for safety assessment. The problem is estimating the snow load, which appears to be ununiformly distributed on the structure. Similarly to [16], the load is estimated based on the deformation of the structure. This time, the structure is divided into smaller areas with a uniform load. Then, the load is assessed, assuming the deflected shape is similar to the load shape. This is the basis for an iterative algorithm Snow Load Identification Processor (SLSS) incorporated within a software aimed at obtaining results in an agreement between measured data and the FEM model. This model has been previously validated based on eigenfrequencies and mode shapes of the real structure. The pre-study with numerical methods helped to determine a minimal number of sensors. Results differed by only 3,5%, a good prognosis for future in-situ studies.

The previously mentioned master thesis [15] also approaches a similar task but achieves an estimated load generally lower than the real one with a significant error, possibly due to insufficient measured points (merely two) and the timber's nonhomogeneous behaviour.

3.3 Accounting for spatial variability

Capturing the spatial variability of loads requires deploying multiple sensors on the slab. Different spatial distributions of applied loads result in distinct deflected slab shapes. Recording multiple measurements of these deflections allows one to back-calculate and infer the original spatial distribution of the loads to a limited extent. Results can then be validated by comparing the measured deflections with the results of numerical methods (such as Finite Element Models) or analytical solutions.

A study on CFRP-strengthened RC slab-beam systems [18] uses standardised load test protocols ACI 437 (monotonic test loading) to assess the effectiveness of strengthening. Dial gages were installed in adequate positions that show maximum deflection (centroid of the area).

Measurements were taken before loading, after each of 4 increments, after 24 hours, and after unloading. The study shows that measuring systems and FEM models (ABAQUS twin of the structure with the test loading) largely agree after proper calibration of both, and the value of deflection obtained in the FEM model was, on average, 0.843 of the actual deflection.

Similarly, the measured deflection agrees with the FEM model both in pre-test and during long-term in-situ monitoring in previously mentioned studies [9, 14]. It needs to be mentioned that these studies present results only for a uniformly distributed load.

3.4 Accounting for temporal variability

One potential gain of using permanently installed SHM for imposed load measurement (as opposed to regularly collecting data at sparse intervals) is the possibility of capturing the temporal variability of the load. Such practice is increasingly common and is now used in early warning systems that help monitor structure deflection.

A previously mentioned study from Canada on timber trusses [14] uses the early warning system to register results in set time intervals. The results are validated through both a FEM model and direct measurements of the load on the system via scales. In case of discrete (but frequent) measurements, the intervals between measurements can be adjusted during monitoring depending on the acquired magnitude of deflection, allowing for more precise results during the most crucial moments of higher load (e.g., peak hours).

In [19], steel warren roof trusses are investigated. Thirty-six fibre optic sensors and a four-channel reading unit are connected to the associated software. The system is based on FBG technology; additionally, independent laser-based systems were selected to monitor the deflection. Sensors were installed on individual truss members and calibrated over one week during the commission. A safety threshold of 75% allowable strain has been calculated in FEM software. Data from SHM was collected every 30 min or 60 min, which allowed for a good representation of the temporal variability of snow and entertainment loads. Results from monitoring of the arena agree with data collected in a log of snowfall events (including time and snow depth) and a log of events at the venue.

A study on a timber truss in Canada [20] aimed to determine the sensitivity of sensors to load by measuring deflection with FOS (operated by Optical) and strain gauges (Datascan and Quantum X). A gravitational load was applied in the middle of the span, and measurements noted an increase in deflection at the time when the load was applied; however, no quantitative relationship between measurements has been found.

3.5 Accounting for additional confounding factors

Besides the applied loads, various phenomena and environmental factors can affect deflections and strains, such as temperature, humidity, and creep. While temperature effects are not particularly relevant for slabs in buildings (which typically experience stationary temperatures throughout their design life), the influence of the other factors may be intensified due to their short spans and more complex structural forms (two-way plates, unclear boundary conditions). Multiple studies show that, despite the influence of such effects, it is possible to capture load changes by measuring slab deflections or strains. For example, [9, 11] mention a wide range of temperature and humidity sensors that are necessary in the case of monitoring timber structures. Furthermore, [14] uses a control point to subtract the moisture-induced strain

of the column on which the ATM is mounted from the measured deformations and sorption method to calculate theoretical shrinkage or swelling caused by varying moisture content.

Especially interesting in this context is a study of the effect of crowd load on the beams of a heritage timber building [21] with significant yearly maximum temperature amplitudes. Fiber Bragg Grating (FBG) sensors are installed at key load-transfer locations — areas notably affected by crowd presence and where damage could result in substantial deformations. It is assumed that the measured strain consists of two primary components: temperature-induced strain and crowd-induced strain, while other environmental influences (e.g., wind, snow, and humidity) are considered negligible. To isolate the crowd-induced strain, the researchers first calibrate a relationship between temperature and temperature-induced strain using data collected during periods without tourist activity. This calibrated relationship is then applied to subtract the temperature effect from the total measured strain during occupied hours. With strain data recorded hourly over a span of more than seven years, the study successfully identifies the annual load distribution, highlighting peak crowd-loading periods and enabling insights into the most critical structural conditions.

The spatial variability of strain or deflection can also depend on other actions or conditions, as demonstrated in the previously mentioned case of a timber truss in Canada subject to a point load [20]. The acquired deflection varied among different wooden trusses under similar loads even despite attempts to remediate the gauges' temperature sensitivity. The cause of this variation was speculated to be the non-homogeneous material behaviour and cracks; however, there is no detailed analysis to identify the source of variation.

Another time effect is the creep or plasticising of materials, which SHM sensors can capture. This phenomenon can affect the results, potentially obscuring the actual loading conditions. For instance, laboratory tests of FBG sensors [22] demonstrate the effect of creep on long-term monitoring. The beam in [22] is equipped with extensometers and three fibre optics laminated inside the beam, each containing three FBG sensors. Tests with the same loading arrangement were performed three times at 1-year intervals. Strain increased each year, successfully capturing the decrease in the elastic modulus of timber over two years. Finally, during a study on a newly casted concrete slab [23], deflections are used as a proxy for construction loads. The inelastic behaviour of the slab during hardening and residual deflection after unloading are captured. However, no quantitative relationship between load and displacement is observed in this case. Regular system calibration could mitigate this problem.

3.6 Summary

The previously mentioned studies use a several types of sensors, with strain gauges and FOS being the most popular. The different systems are summarised in the Table 2.

Table 2. Comparison of measurement systems

Measurement system	Measurand	Number of sources	Comments	Reference
Gauges	Strain	8	Local measurements, continuous in time, reliable, difficult installation, low cost	[9–11, 14, 15, 18, 20, 23, 24]

Fiber Optic Sensors	Strain	7	Distributed measurement, continuous in time, difficult installation	[9–11, 19–22]
Monitoring stations	Deformation	4	Local measurements, continuous in time, easy installation, high cost	[9, 13, 14, 17]
LVDT	Deformation	3	Local measurements, continuous in time, reliable, accurate, difficult installation	[9, 14, 16]
Potentiometers	Deformation	1		[15]
Inclinometers	Inclination	1		[12]
MEMS	Inclination	1		[16]
Accelerometers	Acceleration	1		[24]
Comparison of multiple methods		3		[9, 11, 13]

4 DISCUSSION

SHM systems are commonly used for load assessment in bridges. Still, despite their capacity to capture strain or deflection changes in time and relative popularity for damage assessment, they are not equally well-received as a method for estimating imposed loads on buildings. In the following, we summarise the findings from our literature study on using SHM for load measurements on buildings.

Many studies have explored the relationship between the measurand – typically strain or deflection – and the applied load. Most of these investigations focus on the long-term monitoring of roofs subjected to snow loads. Validation of such a relationship is performed either by comparison with direct measurements of the loads (e.g., via scales mounted on the roof in the case of snow load) or by comparison with the result of FEM, assuming that the structure behaves as expected in a controlled environment. In real-world (in-situ) applications, however, environmental conditions and other confounding factors introduce limitations. These factors can affect sensor performance and distort the relationship between the measured response and the actual load. Therefore, accurate data interpretation requires careful processing and, ideally, collecting additional environmental data – such as temperature and humidity – to support proper correction and calibration.

In the case of buildings and slabs, assessing the spatial variation of the load is complex. An ideal monitoring system must be able to capture different load arrangements. Variability of deflection of beams and trusses under different loading has been shown to agree with analytical or numerical models; however, for slabs, this agreement has been shown only for uniform loads. As for 2D systems, it is possible to measure continuous deflection shape or strain values. However, no known system is able to capture a deflection surface for 3D systems. Therefore, future studies on the optimal placement of sensors on slabs are necessary, for example, by analysing numerical results [9] or concerning the nonhomogeneous behaviour of the material and local damage that might influence the measurements.

One of the most significant advantages of a permanently installed Structural Health

Monitoring (SHM) system is its ability to capture the temporal variability and intermittent nature of imposed loads. The growing adoption of SHM in early warning systems—where continuous monitoring is used to detect the exceedance of critical thresholds—demonstrates that real-time tracking of load changes is both feasible and increasingly reliable. In the case of discrete but frequent measurements, different time intervals of the measurements might be set to optimise the accuracy of the captured changes and the amount of data to post-process. This is done by defining certain thresholds for which the measurement should be more frequent or continuous. However, regular system calibration is essential to provide the most accurate data and monitor the effects of creep and material plasticisation.

In summary, calculating simpler load distributions based on deflection and strain measurements has been done previously (e.g., using polynomial fitting and FEM iteration); however, the use of such methods is limited by the ill-posed nature of the inverse problem, sensitivity to measurement errors, and the need for well-defined boundary conditions. In real-world applications, these challenges are compounded by environmental variability and incomplete data, often requiring extensive calibration, data filtering, and complementary measurements to ensure reliable results. However, the ideas investigated in this paper show potential for further development and implementation in future studies. Then again, complex load arrangements might be difficult to identify using SHM data alone, especially since measurement errors might influence the resulting deflection shapes. However, recent advancements in machine learning offer promising tools for exploring the complex, non-linear relationships between measurands and applied loads. Finally, while factors such as temperature, moisture content, local nonlinearities, and long-term effects like creep can significantly influence the measurements, several studies have demonstrated that these effects can be effectively filtered out or corrected through data processing techniques, allowing the underlying load response to be successfully isolated.

5 CONCLUSIONS

As illustrated, all the components necessary for developing a correct probabilistic load model are present, including spatial and temporal variability that aligns with the load and analytical or numerical models. While synthesising previous experiences may be feasible, the model might not be as precise due to the challenges of accurately identifying complex load arrangements and the influence of other factors on the results.

In conclusion, this approach to load monitoring could be effective, particularly when used alongside multiple sensors and other surveying techniques. It is undoubtedly interesting to pursue further study that might include several tests aimed at monitoring and identifying load-induced and environmentally-induced strain or deflection. Several sensor technologies might be compared, and those most suitable might be chosen for further in-situ testing under first controlled and later uncontrolled loading.

6 ACKNOWLEDGEMENTS

The study is sponsored by Formas grant 2022-01227. The support of this study by Tyréns Sverige AB is also gratefully acknowledged.

REFERENCES

- [1] Lars Sentler. *Live load surveys - a review with discussions*. 78, Lund, Sweden: Lund Institute of Technology, 1976.
- [2] Culver CG. Live-load survey results for office buildings. *ASCE J Struct Div* 1976; 102: 2269–2284.
- [3] Asantey SBA, Andam KA. Factory and warehouse live load survey. *Building and Environment* 1996; 31: 167–178.
- [4] Corotis RB, Harris JC, Fox RR. Delphi methods: Theory and design load application. *Journal of the Structural Division* 1981; 107: 1095–1105.
- [5] Li Y, Chen J. Structural live load surveys by deep learning. *Smart Structures and Systems* 2022; 30: 145–157.
- [6] Wu W, Dou K, Xu C, et al. Floor live load survey and modelling by house VR viewing and public registration information. *Journal of Building Engineering* 2024; 98: 111379.
- [7] Ebrahimpour A, Hamam A, Sack RL, et al. Measuring and Modeling Dynamic Loads Imposed by Moving Crowds. *Journal of Structural Engineering* 1996; 122: 1468–1474.
- [8] Fritz H, Walther C, Kraus M. Piezoresistive Sensors for Monitoring Actions on Structures. In: Rizzo P, Milazzo A (eds) *European Workshop on Structural Health Monitoring*. Cham: Springer International Publishing, 2023, pp. 123–133.
- [9] Helmer-Smith H, Vlachopoulos N, Dagenais M-A, et al. Comparison of multiple monitoring techniques for the testing of a scale model timber Warren truss. *FACETS* 2021; 6: 1510–1533.
- [10] Kim N-S, Cho N-S. Estimating deflection of a simple beam model using fiber optic Bragg-grating sensors. *Experimental Mechanics* 2004; 44: 433–439.
- [11] Palma P, Steiger R. Structural health monitoring of timber structures – Review of available methods and case studies. *Construction and Building Materials* 2020; 248: 118528.
- [12] Kinasz R, Bereza W. Control of building safety through snow load monitoring. *Budownictwo i Architektura* 2024; 23: 191–204.
- [13] Kovačić B, Kamnik R, Solovev V, et al. The Comparison of Measuring and Computing Results of Construction Vertical Displacement. *Procedia Engineering* 2016; 165: 926–935.
- [14] Helmer-Smith H, Dagenais M-A, Vlachopoulos N. Long-term deflection monitoring of a heritage, timber truss structure, and development of an integrated emergency alarm program. *Journal of Civil Structural Health Monitoring* 2023; 13: 1023–1041.
- [15] Doggett C. Measurement Systems for Estimating Imposed Loads. (2022), <http://lup.lub.lu.se/student-papers/record/9094583> (2022, accessed 14 January 2025).
- [16] Martinez M, Rocha B, Li M, et al. Load monitoring of aerospace structures utilizing micro-electro-mechanical systems for static and quasi-static loading conditions. *Smart Mater Struct* 2012; 21: 115001.
- [17] Zóltowski K, Drawc M. Inverse Analysis as a Key Element of Safety Assessment under the Snow Load For The Large Suspension Roofs Structure. *Archives of Civil Engineering; Vol 66; No 2; 369-383*, <https://journals.pan.pl/dlibra/publication/131815/edition/115145> (accessed 26 February 2025).

- [18] Hanoon AN, Abdulhameed AA, Al-Zuhairi AH, et al. Strength Evaluation of CFRP-Strengthened RC Slab-Beams System by Load Test to Satisfy the Safety Requirements: A Case Study. *Int J Civ Eng* 2024; 22: 1871–1891.
- [19] Limaye V, MacDonnell R, Nickerson P, et al. SHM application for managing snow load risks for indoor arenas.
- [20] Locklin L, Orellana J, Akhras G. Monitoring wooden Warren truss hangar to extend their design life. *J Civil Struct Health Monit* 2017; 7: 263–274.
- [21] Tianhao Li NY. Condition assessment of timber beam in a typical Tibetan heritage building under crowd load. *Advances in Structural Engineering* 2021; 24: 1910–1925.
- [22] Čápková K, Velebil L, Včelák J, et al. Environmental testing of a FBG sensor system for structural health monitoring of building and transport structures. 2019, pp. 726–733.
- [23] Kigoye E, Kyakula M. Load Deflection Relationship of a Solid Slab under the Action of Construction Loads. *Advances in Civil Engineering* 2022; 2022: 3125920.
- [24] Brownjohn JM, Pan T-C. Identifying Loading and Response Mechanisms from Ten Years of Performance Monitoring of a Tall Building. *Journal of Performance of Constructed Facilities* 2008; 22: 24–34.