Evaluation of Real-Time Load Path Monitoring for Mullion-Transom Façades

Nathalie Nießer, Geralt Siebert

University of the Bundeswehr Munich, Institute for Structural Engineering, Germany
nathalie.niesser@unibw.de; geralt.siebert@unibw.de

Abstract

The trend toward transparent façades reflects a growing demand for clarity and functionality in architecture, sparking interest in using glass as cladding material and structural stabilisation, particularly for shear bracing in buildings. Mullion-transom façades present a specific challenge, as even slight building deformations can affect the façade structure and its fixings. A thorough understanding of these system interrelationships and ongoing monitoring of the actual load-bearing capacity is essential to ensure the long-term stability of glass as a load-bearing element.

As part of a research project at the University of the Bundeswehr Munich, a cutting-edge test rig was developed to analyse the load-bearing capacity and feasibility of a structural glass façade under dynamic loads. The project aims to create a digital twin of a load-bearing glass façade using numerical models and sensor data. Central to this effort is the measurement of stresses through fibre-optic sensors, which leverage the strain sensitivity of optical fibres. These sensors are applied to the glass surface to record and analyse real-time load paths and deformations under wind loads. This innovative load path measurement system is presented for the first time and assessed for suitability in long-term applications.

This research establishes a critical foundation for the reliable and continuous monitoring of load-bearing glass façades, providing practical insights that support the sustainable integration of these structures in modern façade systems. The findings of this study will contribute to the development of safer and more reliable glass façades, enhancing the overall structural integrity of buildings.

Keywords

Real-Time Monitoring, Load Path Analysis, Load-Bearing Glazing, Mullion-Transom Façades, Fibre-Optic Sensors

Article Information

- Published by Glass Performance Days, on behalf of the author(s)
- Published as part of the Glass Performance Days Conference Proceedings, June 2025
- Editors: Jan Belis, Christian Louter & Marko Mökkönen

1. Introduction

Monitoring structural systems is a core element of system evaluation and enables the quantification of deformation, temperature, humidity, and load paths (Becker, Weisbrich, Euteneuer, Wu & Neitzel, 2014). The demand for advanced sensor networks grows with increasing building size and complexity. These systems incorporate sensors that detect mechanical stresses and process the data digitally (Botts, Percivall, Reed, & Davidson, 2006).

Modern sensing technologies enable real-time acquisition, standardisation, and analysis of measurement data. This improves data comparability and reduces evaluation complexity (Resch, 2012). Direct visualisation of recorded values allows for condition assessment, while continuous data processing enhances the reliability and safety of structural systems.

Nevertheless, data acquisition presents technical challenges. Sensors are often installed in inaccessible areas or over long distances, limiting spatial resolution and potentially missing critical changes (Stewart, Aminossadati, & Kizil, 2017). Environmental influences further affect sensor stability and service life (Becker et al, 2014).

Monitoring load-bearing glass façades is particularly demanding. Mullion-transom systems increasingly integrate stiffening glazing to improve load distribution. These elements perform structural functions and require continuous monitoring due to high mechanical loads. Fibre-optic sensors offer a solution by enabling high-precision, long-term deformation measurements. They allow real-time monitoring of shear stresses in stiffening glass elements. While CFD and FEM simulations predict wind-induced load distributions and deformations, they cannot fully represent real-world conditions. Complex force distributions and dynamic loading demand simulation and measurement data integration.

This study presents a real-time monitoring approach for load paths in mullion-transom façades. The integration of numerical simulation and experimental measurements aims to enable the continuous adaptation of models to actual loading conditions.

Chapter 2 outlines the structural behaviour of load-bearing glass façades and focuses on the mechanics of diagonal block supports as a practical load transfer solution. Chapter 3 introduces digital twins as sensor-coupled simulation tools for adaptive monitoring and predictive assessment.

Chapter 4 details the experimental setup, including the design of a full-scale test rig with fibre-optic sensor integration for capturing strain data under simulated wind loads. Chapter 4.1 describes the test stand and sensor application, while Chapter 4.2 presents the CFD-based wind load simulation and comparative model evaluation.

Chapter 5 discusses the results, with particular attention to the performance of fibre-optic sensors and the predictive capabilities of various turbulence models. Finally, Chapter 6 summarises the findings, evaluates the proposed hybrid monitoring approach, and outlines its potential and limitations for façade system analysis.

2. Glass Façades as Load-Bearing Components

Previous studies have investigated various load-bearing glass systems, including block supports, point fixings, adhesive connections, and hybrid combinations (Neumer, 2018). These concepts were initially implemented in single-story buildings, marking the first applications of load-bearing glass façades. However, this study presents a comprehensive examination and elaboration on diagonal block support, offering a detailed understanding of this structurally efficient and economical solution. This support principle enables an even load distribution along the glass edge. The investigated system consists of three main components, as illustrated in Figure 1 (right):

- Infill Element: The glazing absorbs loads via a compression diagonal.
- Connectors: These transfer loads and ensure a force-fit connection between the glass and the frame (Neumer, 2018).
- Frame Structure: This component redirects the introduced forces into the overall load-bearing system and is based on a mullion-transom configuration.

Furthermore, the implementation of this load transfer mechanism requires the development of appropriate mechanical prestressing elements within the connectors. These elements must apply a defined and sustained prestressing force to the glass panel. This force should be introduced using a simple and efficient mechanism. In the system investigated, this is achieved by tightening screws, which move the prestressing block upward and thereby establish the desired stress state in the glass panel. This principle is illustrated in Figure 1 (left) (Freitag & Wörner, 2011).

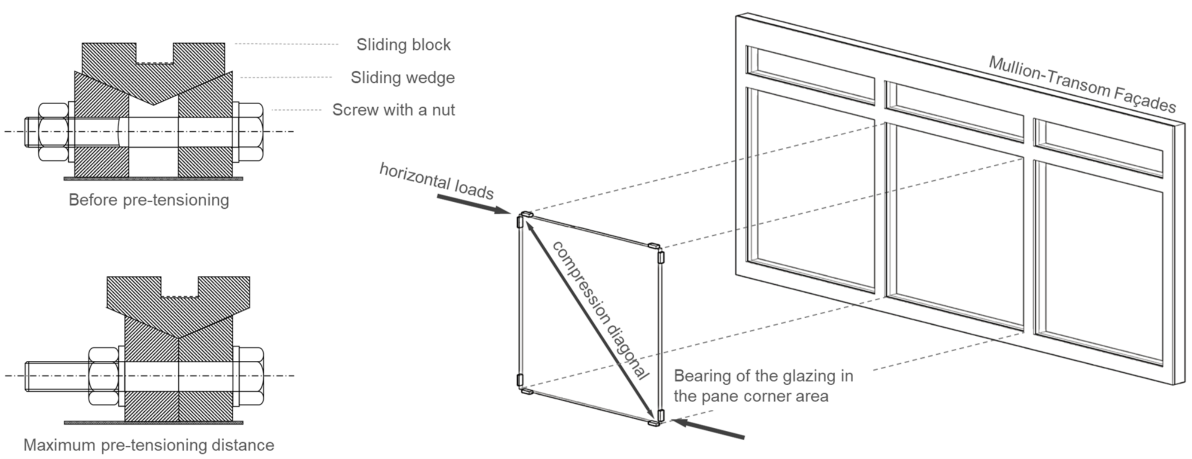

Fig. 1: Stiffening of Mullion-Transom Frameworks with Timber-Glass Composite Elements (Edl, 2008), (Freitag & Wörner, 2011).

External actions must also be considered part of the overall load transfer mechanism, with wind representing one of the most critical loads acting on façade systems. A detailed investigation of its aerodynamic effects is, therefore, essential. Wind loads depend on several factors, including the geometric dimensions of the façade, its position within the building structure, and the surrounding environment (Neumer, 2018).

According to Neumer (2018), the loads acting on the investigated system can be categorised into three main types. Vertical loads result from the self-weight of structural components located above the glazing. However, these are absorbed by the frame structure and are, therefore, not relevant to the stiffening function of the glass. Horizontal loads perpendicular to the glass plane include wind pressure, temperature-induced stresses, pressure differentials, and beam-induced forces. These loads significantly influence the stiffness of the glazing. In contrast, horizontal loads acting within the plane of the glass mainly arise from wind effects and column misalignments and affect the internal load paths within the façade system.

3. Integration of Digital Twins for Structural Monitoring of Glass Façades

According to Wittmeir, Oettl, and Schilp (2023), digital representations can be classified based on the direction and automation of data flow between the physical and virtual instances (see Figure 2). A digital model captures a static representation of a physical object and must be updated manually. A digital shadow enables automated data transfer from the physical object to the digital model but lacks feedback to the physical system. The digital twin constitutes the most advanced form, featuring bidirectional and automated communication between both instances. This configuration enables continuous monitoring and active control of the physical system based on the data collected, analysed, and processed within the digital environment.

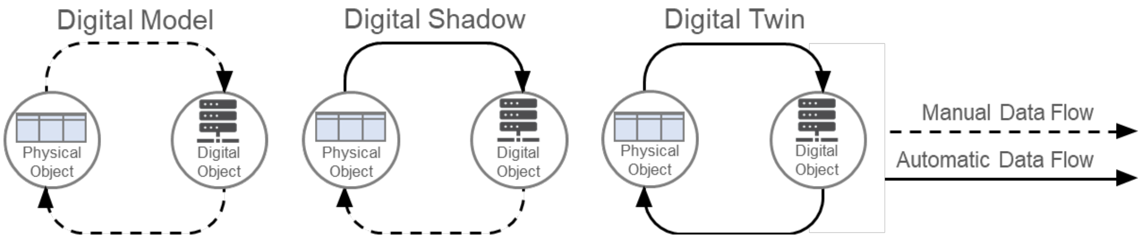

Fig. 2: Schematic Representation of the Digital Twin (Frick & Metternich, 2022).

By integrating sensor data with numerical simulation models, the digital twin enables detailed analyses of mechanical stresses, material behaviour, and load paths. It functions as a central data platform by consolidating heterogeneous information from sources such as CFD and FEM simulations, sensor networks, and inspection records, thereby supporting a comprehensive evaluation of structural integrity (Braml et al, 2021).

This capability is particularly relevant for the monitoring of façade structures. In contrast to static digital models, the digital twin maintains continuous interaction with the physical glass façade. This enables real-time detection of deformations and shear forces, allowing for precise assessment of their influence on structural stability. The combined use of sensor data and simulation models facilitates the early identification of anomalies, improves the planning of maintenance measures, and contributes to the overall enhancement of structural safety.

4. Experimental Study of a Load-Bearing Mullion-Transom Glass Façade

Building on this conceptual foundation, the developed approach for monitoring bracing glass façades is currently being validated on a large-scale test stand. The following section presents the test setup, sensor system, and simulation model.

4.1. Design and Setup of a Test Rig Utilizing Fiber-Optic Sensors

A specially designed test rig has been developed to investigate the load-bearing behaviour of glass façades under dynamic loading. It consists of an earthquake simulation platform and a test setup configured as a timber-glass truss structure with a base area of 7.8 × 12.5 m and a ridge height of 7.5 m. The test element includes twelve bracing glass elements integrated into a mullion-transom façade with multiple measurement points. The bracing elements within the mullion-transom façade are highlighted in Figure 3.

The structure is anchored using HEA400 profiles that are directly connected to the shake table. The earthquake simulation is based on a steel substructure with six support blocks carrying a shake table capable of horizontal displacements of up to 250 mm in both x- and y-directions. These displacements are generated by hydraulic actuators operating with variable frequencies and amplitudes.

To enable comprehensive monitoring of structural loads and environmental influences, the test setup is equipped with the following sensor systems:

- Pressure Sensors: Measure localised loads on the façade structure.
- Strain Gauges: Detect local strains and stresses within the façade elements.
- Fiber-Optic Sensors: Enable long-term monitoring of structural deformations and load paths.
- Temperature Sensors: Record thermal influences on the façade structure.
- Weather Stations: Measure wind speed, direction, and atmospheric conditions.
- Moisture Sensors: Monitor material moisture within the façade elements.
- Thermal Wires: Positioned at strategic points to analyse temperature-induced deformations.

The collected sensor data enables continuous calibration of the façade's digital twin and supports a more accurate analysis of structural behaviour. A reliable predictive model for future loading conditions can be established by systematically recording the structural response.

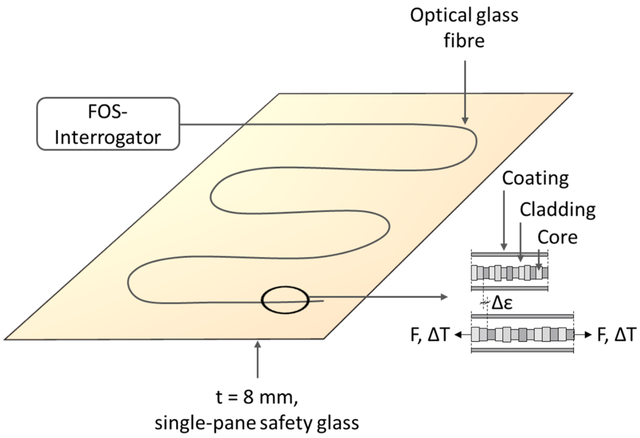

Fig. 3: Test Rig Configuration with Bracing Glass Elements and Fiber-Optic Sensor Placement.

Among the various sensor types, fibre optic sensors are particularly well suited for monitoring bracing glass façades. Their compact form, with a diameter of approximately 0.2 mm, and their transparency make them nearly invisible when applied to glass surfaces (Weimar & Hammer, 2021). Furthermore, fibre optic sensors do not require extensive wiring at each measurement point, which is especially beneficial in high-density measurement applications.

Fibre optic sensors provide high-resolution strain data, capable of detecting variations as small as 1 µm/m. A single optical fibre enables continuous strain measurement over extended distances, with current systems allowing lengths of up to 70 m and spatial resolutions in the millimetre range. This effectively replaces thousands of discrete point sensors and enables the acquisition of continuous strain profiles along bracing glass panels. As a result, local stress concentrations can be detected even at previously unknown locations (Samiec, 2011).

Fibre optic sensors detect changes in light properties within optical fibres caused by mechanical or thermal stress. According to Samiec (2011), Rayleigh-based distributed sensing uses continuous backscattering along the fibre as a measurement signal. Due to manufacturing tolerances, each fibre exhibits a unique and random scattering pattern that remains constant and reproducible under stable conditions. This characteristic pattern shifts along the fibre axis when the fibre is subjected to strain or temperature changes. The sensor unit divides the backscattered signal into small sections, typically one millimetre, and determines the frequency shift for each section to realign the scattering pattern. Based on these frequency shifts, local strain or temperature variations can be derived (Samiec, 2011). The measurement speed also meets the requirements of typical load changes in façade applications. All points along the fibre can be interrogated simultaneously at rates of up to 5 Hz (Samiec, 2011). This allows for a reliable detection of time-dependent deformations caused by wind loads or temperature fluctuations.

To ensure reliable strain measurement, the sensor fibre must be mounted directly onto the glass surface in a manner that guarantees effective load transmission. After cleaning the glazing, a thin adhesive film is placed along the fibre's intended routing, as described by Fildhuth (2015). The sensor fibre is then embedded in the adhesive layer and precisely aligned. UV curing acrylic or epoxy adhesives provide sufficient working time for positioning and cure within seconds under UV light. Alternatively, cyanoacrylate adhesives can be used, which polymerise at room temperature through moisture absorption (Weimar & Hammer, 2022). These adhesives create a stiff yet elastic bond between the glass and the polyimide-coated sensor fibre (Weimar & Hammer, 2021). The adhesive connection enables nearly complete strain transfer to the fibre, achieving transfer efficiencies of approximately 99 %. In tensile tests with strain levels up to 400 µm/m, residual deviations of only 4 to 6 µm/m were observed, corresponding to an error rate of around 1.5 % (Weimar & Hammer, 2021).

4.2. CFD-Based Investigation of Wind Flow and Load Transfer on the Test Rig

In practice, wind loads are often determined based on building regulations or wind tunnel tests, which may lack the spatial resolution and adaptability required for complex façade geometries (Cheng, Huang, Yang & Zhou, 2020). However, a comprehensive assessment of wind effects on glass façades requires a combination of experimental measurements and numerical simulations. As outlined above, fibre-optic sensors provide high-resolution data on structural stresses and are essential for validating numerical models and enhancing their predictive capability. Computational Fluid Dynamic (CFD) simulations are carried out to complement the sensor-based measurements and enable the development of a digital twin capable of predicting load paths within the bracing elements of the mullion-transom façade.

Initially, the computational domain for the simulation of the entire system is defined. According to established guidelines, for a building of height H, the domain should extend approximately 5H upstream, 15H downstream, and 5H laterally to ensure undisturbed inflow conditions and realistic wake development (Dagnew & Bitsuamlak, 2013). In the vertical direction, the upper domain boundary should be located at least 3–4H above the building for low blockage ratios and can be extended up to 10H to further reduce blockage effects (Dagnew & Bitsuamlak, 2013). At the domain inlet, an atmospheric boundary layer wind profile is applied. The lateral and upper boundaries are defined as symmetry or outflow conditions to avoid artificial gradients in the crosswind direction. Solid surfaces, such as the ground and the façade, are modelled with no-slip boundary conditions (Dagnew & Bitsuamlak, 2013). A model of this setup is shown in Figure 4 and serves as the basis for a physically realistic evaluation of wind-induced pressures and forces acting on the bracing glass façade.

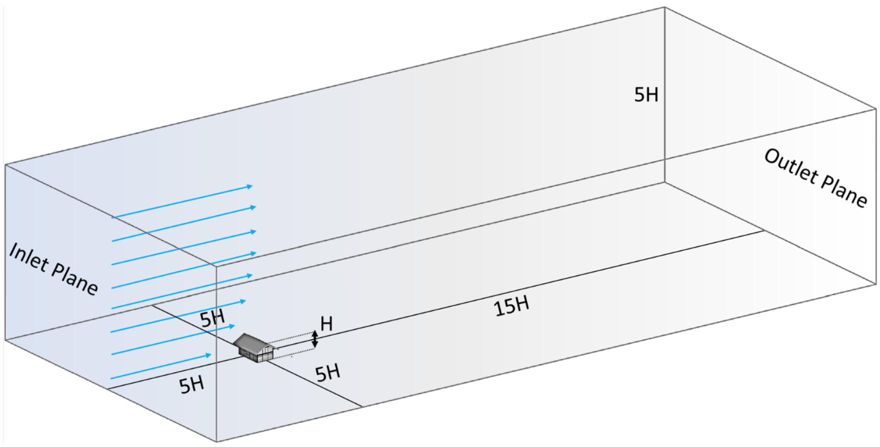

Fig. 4: CFD Domain Setup Based on Geometric Multiples of Building Height (H).

The turbulence model is selected alongside the definition of the computational domain. Common approaches include Reynolds-Averaged Navier-Stokes (RANS), Large Eddy Simulation (LES), and hybrid RANS–LES methods.

RANS solves the time-averaged Navier-Stokes equations, capturing the mean flow field while modelling all turbulence scales (Blocken, Stathopoulos, Carmeliet, & Hensen, 2011). This method is computationally efficient and widely used in engineering applications (Liu & Niu, 2016), but it cannot resolve transient flow structures (Blocken et al, 2011).

In contrast, LES resolves large turbulent structures directly and models only small subgrid-scale eddies (Blocken et al, 2011). It captures unsteady phenomena, such as vortex shedding and flow separation, with higher accuracy. The method requires fine grids and small time steps, especially near solid boundaries, resulting in high computational cost (Dagnew & Bitsuamlak, 2013).

A suitable compromise between accuracy and computational efficiency is offered by hybrid RANS–LES methods. These approaches combine the robustness of RANS near solid boundaries with the higher accuracy of LES in regions dominated by flow separation and large-scale turbulence. Detached-Eddy Simulation (DES), for example, applies RANS modelling close to walls and switches to LES in free shear flows and separated regions (Dagnew & Bitsuamlak, 2013).

To evaluate the aerodynamic behaviour of the bracing glass façade, the present study employs a steady-state RANS turbulence model. In the windward-facing areas of the façade, the RANS model provides reliable predictions due to the attached nature of the flow. A high stagnation pressure develops in this region, which is realistically captured by the RANS simulation. Flow separation, however, becomes critical, particularly at façade edges and on the leeward side. The standard k-ε model tends to overpredict turbulent kinetic energy near stagnation points. This results in premature reattachment of the flow and an underestimated extent of separation and recirculation zones (Blocken et al., 2011). Moreover, RANS models often underpredict turbulence intensity in the wake region, leading to an overly laminar representation of the flow field (Blocken et al, 2011). These effects are illustrated in Figure 5.

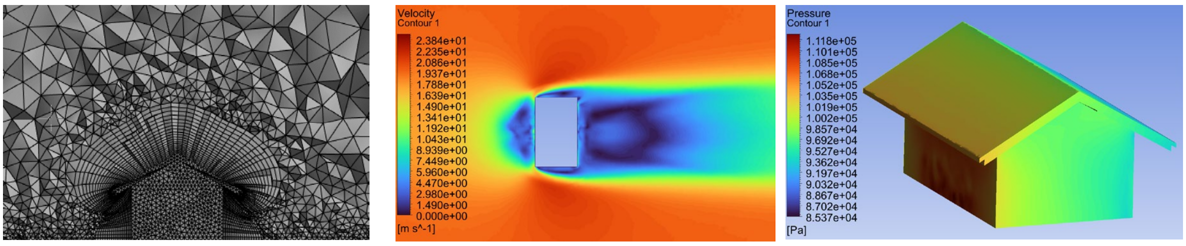

Fig. 5: Example calculation of wind speed at 20 m/s - left: Meshing, centre: Velocity Map, right: Pressure Zones.

Nevertheless, this approach enables an initial approximation of wind loads on the façade with low computational effort. Although RANS models cannot resolve transient flow phenomena or complex separation patterns, they provide reliable predictions of mean pressure distributions in regions with predominantly attached flow (Blocken et al, 2011). As such, they are suitable for a first assessment of the general aerodynamic response of the façade system.

5. Discussion of Results

This study demonstrates the potential of integrating fibre-optic sensor technology and CFD simulations to monitor load paths in mullion-transom façades with stiffening glazing. The results confirm that fibre-optic sensors enable high-resolution strain measurements and offer reliable insight into the mechanical behaviour of glass elements under dynamic wind loads.

A key finding of this study is the importance of validating numerical models with experimental data. While steady-state RANS models offer a computationally efficient approach for estimating mean pressure distributions, they tend to underestimate pressure fluctuations and shear forces. This can lead to notable inaccuracies in load path analysis, especially in areas with flow separation and increased turbulence. However, this approach remains sufficient for initial assessments and model initialization.

The integration of experimental and numerical methods within a digital twin framework allows for adaptive model updates and supports the development of predictive monitoring systems. This hybrid approach lays the foundation for the long-term structural assessment of load-bearing glass façades and contributes to their safe and reliable application in contemporary architecture.

6. Conclusion

This study demonstrates the feasibility of integrating fibre optic sensors and CFD simulations for load path analysis in mullion-transom façades with stiffening glazing. The combination of experimental strain measurements and numerical wind load simulations enables a detailed and accurate assessment of wind-induced structural behaviour.

The findings highlight the fibre optic sensors' high spatial resolution and measurement accuracy, which allow real-time strain monitoring and direct observation of mechanical stresses within the façade structure. CFD simulations—particularly those employing LES and hybrid DES models—provide accurate predictions of wind pressure distributions and load variations across the façade. However, steady-state RANS models exhibit limitations, often underestimating pressure fluctuations and shear forces, which may lead to inaccuracies in load path evaluation. Nevertheless, RANS models are suitable for initial approximations and model initialisation due to their computational efficiency.

Validating CFD results with fibre-optic sensor data enables the detection of deviations between numerical predictions and actual structural responses. This improves the accuracy of the simulation models and allows for their integration into a digital twin. The combined use of measurement data and numerical analysis forms the basis for real-time, predictive monitoring and supports the long-term assessment of load-bearing glass façades in practical applications.

Acknowledgements

This research paper is funded by dtec.bw - Digitalization and Technology Research Center of the Bundeswehr, which we gratefully acknowledge. dtec.bw is funded by the European Union - NextGenerationEU.

References

Becker, T., Weisbrich, S., Euteneuer, F., Wu, C., & Neitzel, F. (2014). Neue Möglichkeiten in der Bauwerksüberwachung durch integrierte Analyse von Sensormessungen und 3D-Bauwerksmodell. In: Gemeinsame Tagung der DGfK, der DGPF, der GfGI und des GiN (DGPF Tagungsband 23).

Blocken, B., Stathopoulos, T., Carmeliet, J., & Hensen, J.L.M. (2011). Application of computational fluid dynamics in building performance simulation for the outdoor environment: an overview. Journal of Building Performance Simulation, 4(2), 157–184. https://doi.org/10.1080/19401493.2010.513740

Botts, M., Percivall, G., Reed, C., & Davidson, J. (2006). OGC® sensor web enablement: Overview and high-level architecture. In S. Nittel, A. Labrinidis, & A. Stefanidis (Eds.), GeoSensor networks (pp. 175-190). Springer Verlag. https://doi.org/10.1007/978-3-540-79996-2_10

Braml, T., et al. (2021). Digitaler Zwilling: Verwaltungsschale BBox als Datenablage über den Lebenszyklus einer Brücke. Bautechnik, 98(9), 757-767. Ernst & Sohn.

Cheng, X., Huang, G., Yang, Q., & Zhou, X. (2020). Influence of architectural facades on wind pressures and aerodynamic forces of tall buildings. Journal of Structural Engineering, 147(1), 04020303. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002867

Dagnew, A. K., & Bitsuamlak, G. T. (2013). Computational evaluation of wind loads on buildings: A review. Wind and Structures, 16(6), 629–660. https://doi.org/10.12989/was.2013.16.6.629

Edl, T. (2008). Entwicklung von wandartigen verklebten Holz-Glas-Verbundelementen und Beurteilung des Tragverhaltens als Aussteifungsscheibe (Doctoral dissertation). Technische Universität Wien, Institut für Tragwerksplanung und Ingenieurholzbau.

Fildhuth, T. (2015). Design and Monitoring of Cold Bent Lamination-Stabilised Glass Investigated by Applying Fibre Optic Sensors (Doctoral dissertation). Universität Stuttgart, Institut für Tragkonstruktionen und Konstruktives Entwerfen. ISBN 978-3-922302-39-1

Freitag, C., & Wörner, J.-D. (2011). Verwendung von Glas zur Aussteifung von Gebäuden. Stahlbau Spezial – Glasbau/Glass in Building, 2011, 45–51. https://doi.org/10.1002/stab.201120006

Frick, N. & Metternich, J. (2022). Design models for digital shadows in manufacturing: A systematic literature analysis and expert study. Systems, 12(20), 1-18.

Liu, J., & Niu, J. (2016). CFD simulation of the wind environment around an isolated high-rise building: An evaluation of SRANS, LES and DES models. Building and Environment, 96, 91–106. https://doi.org/10.1016/j.buildenv.2015.11.007

Neumer, D. (2018). Beitrag zur Aussteifung von Gebäuden durch Glas – Konzentrierte Lasteinleitung im Eckbereich (Doctoral dissertation). Universität der Bundeswehr München, Neubiberg: Institut für konstruktiven Ingenieurbau.

Resch, B. (2012). Live Geography - Standardised Geo-sensor Webs for Real-time Monitoring in Urban Environments. Dissertations in Geographic Information Science. ISBN 978-3-89838-664-7

Samiec, D. (2011). Verteilte faseroptische Temperatur- und Dehnungsmessung mit sehr hoher Ortsauflösung. Photonik, Heft 6. AT-Verlag, Fellbach

Stewart, C., Aminossadati, S., & Kizil, M. (2017). Verwendung von Echtzeit-Messdaten zur Simulation dynamischer wettertechnischer Modelle. Mining Report, 153(4), 356–363.

Weimar, T., & Hammer, C. (2021). Anwendung faseroptischer Dehnungsmessung für die experimentelle Untersuchung von Verbundglas. ce/papers, 4(1), 199–208. https://doi.org/10.1002/cepa.1254

Weimar, T., & Hammer, C. (2022). Determination and evaluation of the interlaminar shear modulus of polyvinyl butyral using fibre optic sensors. Glass Structures&Engineering.https://doi.org/10.1007/s40940-022-00200-1

Wittmeir, T., Oettl, F., & Schilp, J. (2023). Digitaler Zwilling für die additive Fertigung. WT Werkstattstechnik, 113(3), 119–123. https://doi.org/10.37544/1436-4980-2023-03-53