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Sensor-Supported Monitoring of Load-Bearing Glazing

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Abstract

In recent decades, the proportion of glass façades in architecture has risen markedly, from complex structures to standardised system solutions. This trend has generated interest in using glass not only as a transparent cladding material but also as a key component of the building's supporting framework, enhancing its overall stiffness. At the University of the Bundeswehr Munich (UniBw M), research is ongoing to understand how glazed elements behave under stress, with the aim of exploring their capacity to develop effective shear and in-plane stiffness. Large-scale tests show that with proper edge stiffening, glass can transfer significant compressive and shear forces, thereby helping to stiffen buildings. Simultaneously, gaps in planning, verification, and inspection practices highlight a pressing need for optimisation in façade technology that cannot be fully addressed by implementing Building Information Modelling (BIM). Consequently, sensor-based monitoring systems are being developed to provide ongoing condition assessments. When combined with a digital twin, which acts as a bridge between measurements and simulations, the goal is to perform smart, condition-based façade monitoring with real-time recommendations for action. This article outlines ongoing research at UniBw M that integrates experimental, numerical, and sensor-based methods to measure the structural role of load-bearing glazing in a full-scale test setup.

Keywords

Stiffening Glazing, Load Path Analysis, Large-Scale Experimental Testing, Digital Twin

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1. Introduction

As a load-bearing building material, glass is increasingly used in the construction industry, especially in response to rising demands for energy efficiency, daylight utilisation, and architectural design (Bedon et al. 2018). At the same time, owing to its low tensile strength, brittle behaviour, and multiple interactions with adjacent components, glass exhibits heightened structural vulnerability. In fact, under exceptional actions, glass facades are considered among the most critical building components (Bedon et al. 2018).

However recent studies have demonstrated that glass elements can contribute significantly to the global structural behaviour of buildings when used as load-bearing components. In particular, composite systems such as glass- timber shear walls have shown that laminated glass can transfer in-plane forces and enhance overall system stiffness under lateral loading (Žarnić et al. 2020). In parallel, research on structural health monitoring has explored the application of multi-sensor systems for façade structures, enabling the acquisition of deformation, load, and environmental data under real operating conditions (Rajčić et al. 2020; Momeni et al. 2024).

These research efforts are often addressed separately. Existing studies predominantly focus either on the structural behaviour of load-bearing glazing under controlled laboratory conditions or on monitoring strategies that are not explicitly linked to the load transfer mechanisms of structural glass systems. As a result, a combined approach that integrates full-scale experimental investigations, continuous sensor-based monitoring, and numerical modelling within a consistent digital framework remains largely unexplored.

Against this background this study aims to extend the current state of the art by linking experimentally validated load-transfer mechanisms of load-bearing glazing with real-time sensor data and a continuously updated digital twin. This enables a condition-based assessment of structural performance under realistic environmental loading and provides a basis for improved evaluation of safety and serviceability during operation.

In this context, wind loading represents one of the governing external actions for glass façades. Numerical and experimental investigations of various façade typologies show that simplified assumptions about wind loads are often insufficient to adequately capture system-relevant structural details in façade design (Bedon et al. 2018). These challenges require early detection of structural changes with high reliability, particularly under real environmental conditions. Early detection of damage in load-bearing structures is of great interest across many sectors, as it provides economic benefits and significantly contributes to safety (Farrar and Worden 2007).

Accordingly, structural health monitoring involves the ongoing or event-based gathering of data on relevant parameters such as deformations, temperatures, moisture levels, or dynamic behaviour (Becker et al. 2014). By deploying sensor networks, changes in a structure's condition can be monitored in real time, during and after extreme events (Becker et al. 2014). Simultaneously, the measurement technology used must continuously withstand environmental conditions on façades and deliver high-resolution and reliable data over long periods. To detect such structural changes, robust data reduction and analysis methods are vital to a sustainable, long-term monitoring strategy (Farrar and Worden 2007).

Based on this, the main goal of the research project is to develop a method for integrating numerical simulations and experimental measurement data into a digital twin, enabling real-time monitoring of load paths in load-bearing glass façades. Consequently, the load-transfer mechanism of the investigated system and the experimental approach for the large-scale component test carried out at UniBw M are first outlined. Next, the monitoring concept and the measurement data collected so far are presented. Based on these findings, it is shown how these measurements can be used to continuously update the digital twin. Finally, the results obtained are discussed and critically evaluated.

2. Structural Role of Load-Bearing Glazing

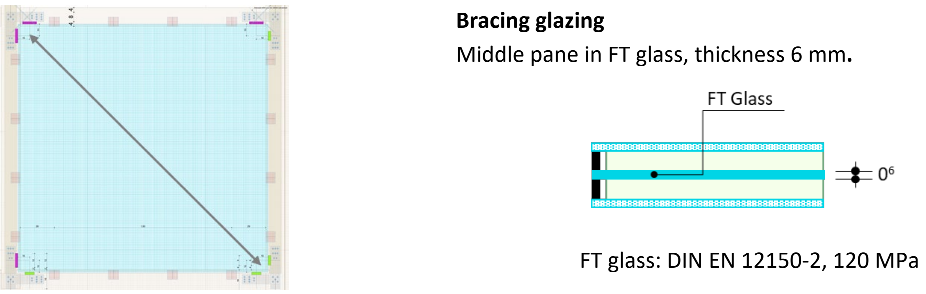
Facades are traditionally classified as non-load-bearing components, which, according to current standards, allows for a certain degree of damage. However, this assumption does not apply to load-bearing glazing systems, as these must not only absorb the loads acting upon them but also compensate for deformations of the primary structure. Consequently, the current normative approach to glass facades tends to underestimate the actual load-bearing function of modern facade systems (Bedon et al. 2018).

Accordingly, the focus is shifting from a purely structural physics perspective to a static-mechanical assessment, in which the fracture mechanics and strength-related properties of glass are of primary importance. Here, fully tempered (FT) glass in particular exhibits the highest strength due to its high surface pressures. In practice, however, this architectural glass often fails even under significantly lower loads. As a result, the experimentally determined tensile strength of glass shows considerable variability, heavily dependent on the test methods used and the surface condition. Overall, extreme actions demand particularly careful material- and system-specific design of glass façades. This emphasises the need for thorough analysis and structural verification, especially when designing for exceptional loads (Bedon et al. 2018).

For the structural design of load-bearing glass facades, it is therefore essential to identify and mechanically characterise the dominant load-transfer mechanism for horizontal forces. Beyond traditional plate action, the development of membrane stress states plays a significant role in overall load-bearing performance. For the following investigations of load transfer, a glass pane is considered in which the stiffening effect is created by the formation of a compressive diagonal. This mechanism occurs here due to special setting blocks in the corners of the panes. In this way, horizontal loads can act in the plane and create a diagonal compressive force within the glass pane. Since these so-called connectors usually only transfer compressive forces and decouple under tensile stress, only the compressive diagonal remains effective as a load-bearing element in the design. Experimental investigations show that such systems develop considerable deformations before failure. These are mainly due to stability phenomena along the formed compressive diagonal. The structural behaviour is thus more influenced by buckling and stability effects of the compression diagonal than by pure material fracture.

Fig. 1 shows the system structure examined in the following analyses. The glass pane is integrated into a wooden frame as a filling element and serves exclusively as a stiffening component by forming the pressure diagonal described above, achieved with a monolithic glass pane that enables form-fitting force transmission at its edges. To meet the building's physical requirements for a façade system, the load-bearing glass pane is positioned as the middle pane of a triple-insulated glazing unit. This configuration provides additional protection for the structural pane against external loads. This load-transfer mechanism has been thoroughly investigated in detail by Neumer (2018).

It should be noted that, for the actual experimental testing, the third outer protective pane was removed for measurement purposes. This decision was made to facilitate direct observation of the deformation behaviour of the load-bearing glass pane using the instrumentation employed. Although this modification alters the building's physical properties, it does not adversely affect the structural load-bearing behaviour of the tested façade system, as the load transfer function remains intact.



Bracing glazing
Middle pane in FT glass, thickness 6 mm.

FT glass: DIN EN 12150-2, 120 MPa

a)

b)

Fig. 1: Test specimen: a) system configuration, b) cross-section of the glazing assembly.

3. Experimental Investigation

The study examined a façade construction in which the loads from the dead weight of the glazing are not transferred to a secondary supporting structure (e.g., mullion-transom construction), but are instead transferred downward within the façade plane or the building shell itself. The glazing thus fulfils a direct load-bearing role in the system.

The aim of this investigation is to analyse the stress distribution of a bracing glass façade under realistic environmental conditions. The main focus is on wind-induced shear actions based on quasi-static load assumptions. Additionally, it should be recognised that exceptional actions such as snow loads, extreme thermal effects, or seismic events may significantly affect the structural performance of load-bearing glass façades and potentially reduce system capacity. Such effects should also be recorded as part of a comprehensive monitoring framework, although this study focuses exclusively on wind load.

This requires a robust sensor network that can withstand long-term environmental conditions and enable continuous, reliable data collection under real-world operating conditions.

3.1. Full-Scale Test Setup

To investigate the stiffening effect of load-bearing glass façades not only under laboratory conditions on individual panes, as was done by Neumer (2018) to analyse concentrated load transfer in corner areas, but also to record the load paths within a real overall system, a large-scale test rig was developed.

For this purpose, a timber-glass truss structure with a floor area of 7.8 × 12.5 m and a ridge height of 7.5 m (Fig. 2b) was built on the former airfield of the UniBw M (Fig. 2a). Twelve load-bearing glass elements were integrated into the supporting structure, which contribute to the absorption and transfer of shear loads into the overall system in accordance with the construction principle described above.

The aim is to experimentally identify and assess the load transfer mechanisms and the structural role of the glass panels within the integrated real system.

a) b) c)

Fig. 2: Test setup: a) Location of test setup, b) View of old runway, c) electric cylinder.

The structural behaviour of the glass façades is analysed under quasi-static loading, with wind as the governing external action. The resulting aerodynamic pressure is given by

$$p(t) = \frac{1}{2}\rho v^2(t) c_p \tag{1}$$

- ρ: air density [kg/m³]
- $v(t)$: time-dependent wind speed in the direction of flow [m/s]
- c_p: aerodynamischer Druckbeiwert (dimensionslos)

and results in a force acting on the loaded surface.

$$F_{wind}(t) = \int_A p\,(t) dA \quad or \quad F_{wind}(t) = p(t) dA \tag{2}$$

- A: area of the façade exposed to airflow [m²]

This value describes the external load but does not include any information about the system's stiffness. It is challenging to determine this value solely from wind load because these loads are stochastic and show spatially uneven pressure distribution, resulting in complex load paths within the structure and a non-immediately deterministic system response.

Nevertheless, to specifically investigate the structural properties, the building is directly connected to a vibrating plate using HEA-400 profiles. The total mass of the system is approximately 110 tonnes. It rests on six bearing blocks with a friction coefficient µ of 0.05. These bearings allow horizontal movement of up to ±250 mm in the x- and y-directions. An electromechanical servo test cylinder is used to excite the test bench mechanically (see Fig. 2c). The linear drive enables controlled application of tensile and compressive forces up to 100 kN, thereby providing defined load conditions on the supporting structure. This excitation subjects the system to impulse-like or dynamic loads. The impact induces dynamic system excitation, activating inertial forces due to acceleration.

The structural behaviour is described by the equation of motion.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = F(t) \tag{3}$$

- x(t): time-dependent shift [m]
- m: effective mass [kg]
- c: damping coefficient [Ns/m]
- k: stiffness [N/m]

To determine the system stiffness, an impact excitation is applied. Following a brief impulse, a free oscillation takes place.

$$m\ddot{x}(t) + c\dot{x}(t) + kx(t) = 0 \tag{4}$$

The measured natural frequency corresponds to a linear single-mass system.

$$k = m\omega_n^2 \tag{5}$$

- ω_n: Natural frequency of the system [rad/s]

This method allows the system stiffness to be determined independently of the wind load. Assuming a quasi-static wind effect, the corresponding relationship between the force induced by the wind and the structural deformation can then be established.

$$kx_{wind}(t) = F_{wind}(t) \quad \rightarrow \quad x_{wind}(t) = \frac{F_{wind}(t)}{k} \tag{6}$$

For a detailed derivation and formulation of the underlying equations, see Eurocode 1 (DIN EN 1991-1-4) and Flay (2013).

3.2. Measurement Concept

The purpose of the measurement equipment is to continuously record relevant structural and environmental influences and the resulting system response. Deformations, strains, and forces are considered key target variables for quantitatively assessing the load-bearing behaviour of the glass façade under real-world operating conditions. Sensor-based recording enables a time-resolved analysis of stress conditions under natural wind and environmental factors. Unlike purely selective tests under laboratory conditions, this method allows the entire system to be examined under changing boundary conditions and real load paths.

Since facades are subject to many structural loads and environmental influences, their behaviour is comprehensively recorded using several sensor systems. Pressure sensors measure local loads on the facade structure, while strain gauges record local strains, from which deformations and internal forces can be derived. Temperature sensors monitor thermal influences in order to analyse temperature-related deformations. In addition, weather stations continuously provide wind speed and direction data. Finally, humidity sensors measure the moisture content of the façade elements.

Table 1: Sensor specifications.

Nr.	Sensor type	Measured quantity	Measuring range	Accuracy
7	Moisture sensor for wood	Wood moisture content (mass-based, %)	0–50 % moisture content (at 23 °C)	±1 % of full scale (FS)
2	Thermowire	Temperature	−10 °C to +105 °C	±2.5 °C or ±0.75 % of reading
4	Weather station	Wind speed	0–75 m/s	35 m/s: ±5 % Root Mean Square (RMS)
12	Pressure sensor	Differential pressure	±1250 Pa	±0.5 % FS
20	Strain gauge	Mechanical strain	±2000 με	±2,6 % (k = 2)
2	Accelerometer	Vibration acceleration	1–100 m/s²	±2 % FS
6	Displacement transducer	Linear displacement	0–100 mm	±0.075 % FS


a) b) c) d)

Fig. 3: Sensor setup: a) weather station, b) humidity sensor, c) pressure sensor, d) shadow of triple and double glazing.

3.3. Load Assessment

The wind load on façades is determined in accordance with Eurocode 1 (DIN EN 1991-1-4), which describes the design procedures for structures up to a height of 200 m and accounts for both global wind effects on the entire structure and local effects on components and their fixings. The reference value is the characteristic 10 minute mean wind speed at a height of 10 m above open terrain. However, the standard provides only limited information on specific structural and façade systems, particularly regarding the consideration of local thermal influences, torsional components, contributions from higher natural modes, and aeroelastic effects. Assessments of extreme storm events show that the actual wind effects can sometimes exceed the normative design values. This means that the limits of simplified wind load approaches for bracing façades are quickly exhausted, so that a differentiated consideration of complex mechanisms of action must be taken into account (Bedon et al. 2018).

A precise assessment of wind effects on glass facades can be achieved by combining experimental measurements with numerical simulations. Beyond sensor-based data, CFD (computational fluid dynamics) simulations are also conducted to identify load paths within the stiffening elements.

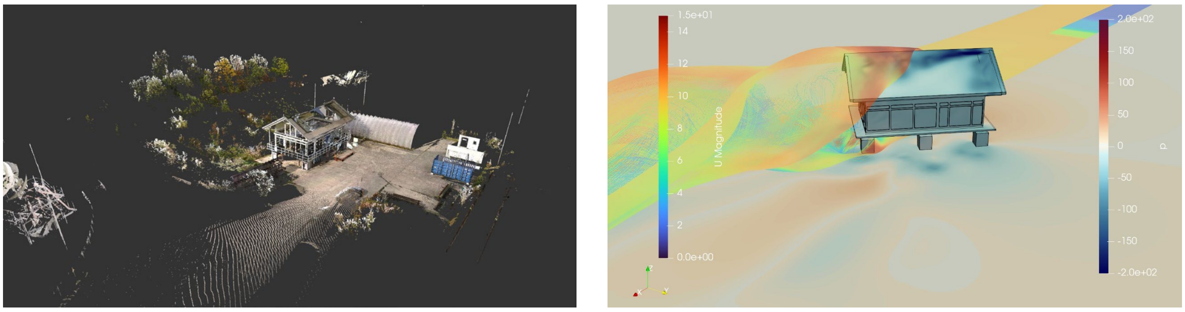
To achieve this, the calculation area for simulating the entire system was defined according to best-practice guidelines for wind analysis around buildings. According to these current guidelines, the calculation area for a building height H should extend approximately 5H upstream, 15H downstream and 5H sideways to ensure undisturbed inflow and realistic wake formation (Dagnew and Bitsuamlak 2013). Vertically, the upper boundary should be at least 3–4 H above the building; however, in special cases, it can be increased to 10H to avoid blocking effects, e.g. to reduce the impact of vegetation or buildings in the surrounding area (Dagnew and Bitsuamlak 2013). An atmospheric boundary-layer profile is used as the standard at the inlet. The lateral and upper boundaries are defined as symmetry or outlet conditions to avoid artificial cross-flow gradients. Finally, solid surfaces such as floors and facades are modelled with non-slip boundary conditions (Dagnew and Bitsuamlak 2013).

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

Hybrid RANS-LES methods provide a compromise between accuracy and computational effort. These combine the robustness of RANS in the near-wall region with the higher accuracy of LES in zones with pronounced flow separation and large-scale turbulence. In detached eddy simulation (DES), for example, RANS is used near the wall, and LES is employed in free-shear layers or detached regions (Dagnew and Bitsuamlak 2013).

Fig. 4b shows such a CFD simulation of wind loads on the building and façades. However, the model used so far was based on an idealised, i.e. largely undisturbed, wind load. These effects are already evident in the measurement data, especially in the recorded wind directions. Smaller buildings and the existing vegetation in the surrounding area cause local turbulence and deflections, which must be considered in more realistic modelling.

To enhance the model, a detailed terrain survey is currently being conducted using 3D laser scanning and photogrammetry within a 15H radius around the building. A section of the terrain model derived from this is shown in Fig. 4a.



a) b)

Fig. 4: Simulation setup: a) 3D terrain model of the surroundings, b) CFD simulation of the airflow around the structure.

To sum up, the wind provides the external load, while the impact test determines the structural stiffness. Only the combination of both approaches enables the calculation of wind-induced deformations of the stiffening glazing and its shear stress under real-load conditions.

4. Digital Twin Concept for Load-Bearing Glazing

Implementing the validation approach developed in this work requires a consistent digital system architecture that integrates simulation, measurement, and model structure. This will create a digital twin that systematically combines numerical load assumptions with real-world system responses and continuously updates them. Fig. 5 illustrates the architecture designed for this purpose.

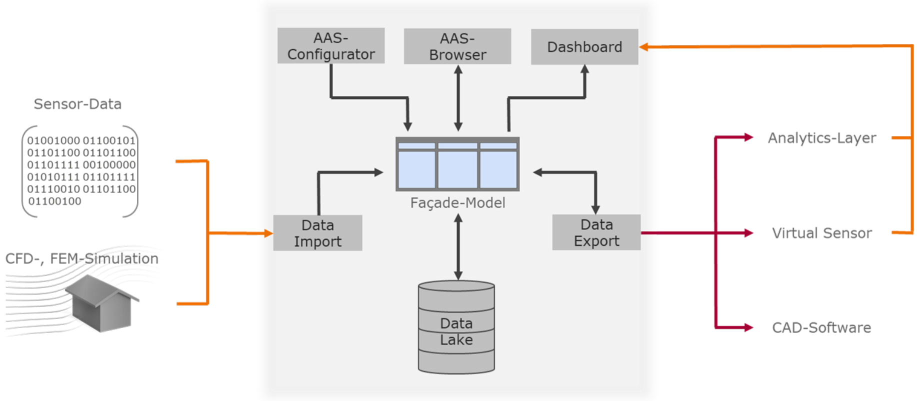


Fig. 5: Concept of the digital twin.

At the centre of the system is a semantically structured façade model that functions as the main representation of the digital twin. This model encompasses the geometric, material, and structural properties of the facade.

The management of this information, along with its clear connection to the relevant façade components, is handled via Asset Administration Shells (AAS). The sensor data generated within this project, together with the associated simulation results, are also organised here. For storage of time-dependent state variables, the model is additionally linked to a data lake. This allows the model to access even old sensor data for retrieval as needed (Schwaninger 2024).

Furthermore, a dependable digital representation necessitates ongoing system updates. Without feedback monitoring, static data storage alone leads to a growing gap between the digital model and the building's actual condition over time (Industrial Digital Twin Association 2024). The method outlined here addresses this issue by using continuously self-updating data and model networks. This connection guarantees that changes in the actual system, such as a change in the stiffness of the remaining glazing due to ageing, are automatically mirrored in the digital model.

This is especially important for glass façades, as local stiffness distributions and nonlinear load redistributions greatly affect their structural behaviour. Reliable assessment of load-bearing reserves and structural integrity during operation is only possible through the continuous integration of real-world measurements and digital simulations.

5. Discussion of Results

Previous studies show that load-bearing glass façades can significantly contribute to the overall stiffening of structures under quasi-static wind loads. Large-scale tests confirm the formation of a compression diagonal in the glass pane. The load-bearing behaviour is less influenced by immediate material failure and more by stability-related effects along this compression diagonal.

In addition to sensor-based measurements of various influencing factors and corresponding numerical simulations that capture load scenarios, the additional impact test provides an independent assessment of effective stiffness. Translating this data into a quasi-static relationship between wind force and deformation creates a reliable basis for assessing shear stress under real boundary conditions. This provides new practical perspectives for the planning, monitoring, and operation of load-bearing glass facades, enabling glazing to be incorporated into the structural design not only as cladding but also as load-bearing glass facades. Continuous sensor-based data collection facilitates a condition-based evaluation of load paths and shear forces, enabling early detection of critical changes. Therefore, the digital twin provides a data-driven foundation for decision-making, thereby establishing the methodological basis for consistent validation of sensor data.

Ultimately, simulation, monitoring, and digital building models of a glass façade can be integrated into a closed control loop, enabling reliable, data-driven evaluation of structural stability under extreme load cases, such as wind loads.

6. Conclusion

This paper shows that load-bearing glass facades can significantly contribute to the overall bracing of buildings. Using a combination of large-scale tests, sensor-based monitoring, dynamic system identification, and CFD simulation, load transfer is analysed not in isolation but within the entire system.

The integrative approach of monitoring and digital twins lays the groundwork for continuous assessment of the structural condition of load-bearing glass facades, adding a condition-focused aspect to the traditional design, which is based solely on norms.

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