Dynamic Identification Techniques for the Vulnerability Analysis of Glass Soft Targets: On-site Vibration Experiments and Numerical Simulations on a Glazed Footbridge

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Abstract The use of glass in buildings as load-bearing material showed an exponential increase. Although it represents a relatively new solution for constructions, requiring appropriate design knowledge, glass is frequently used for facades, roofs, footbridges, etc. Deep care should be certainly spent at the design stage – to ensure reliable *fail-safe* requirements – but also during the life-time of glass structures. The brittle behaviour and limited tensile resistance of material, in addition to the high flexibility of glass assemblies, are responsible of major issues for structural engineers. Further criticalities are represented by time and ambient effects, or extreme loads. The vulnerability assessment of glass structures is hence an open topic, still requiring huge efforts. A combination of multiple aspects should be properly assessed to ensure appropriate protection and mitigation, especially for glazed ***soft targets***. In this paper, dynamic identification methods are used for an in-service glass footbridge. On-site vibration experiments are discussed, including Finite Element numerical analyses, so as to explore the footbridge dynamic performance and assess its vulnerability.

Keywords Structural glass · Vulnerability analysis · Fail-safe design · Soft target · On-site vibration experiments · Finite-element (FE) numerical simulations

3.1 Introduction

Glass is largely used in modern constructions, in the form of facades and windows, roofs, walkways, stairs and load-bearing components in general (see [1–3], see Fig. 3.1). Compared to other (conventional) structural materials for constructions,

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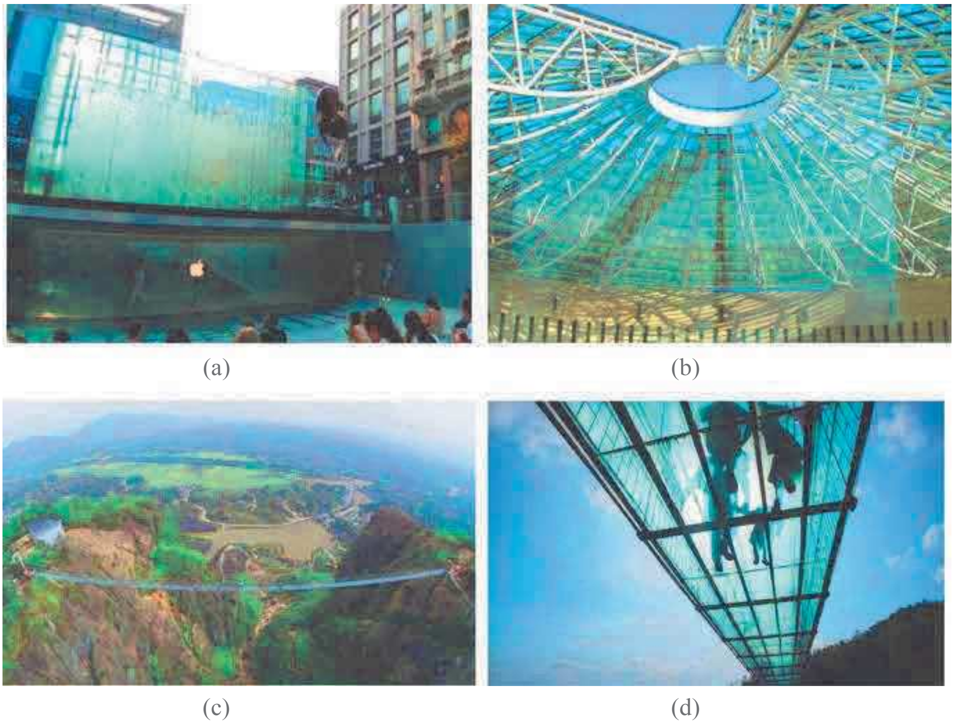

(a) (b) (c) (d)

Fig. 3.1 Examples of structural glass in (a) facades, (b) roofs, (c) and (d) footbridges (www.telegraph.co.uk)

due to the low tensile strength and brittle behaviour, glass structural elements and assemblies are fragile and vulnerable components for constructed facilities. A special design attention is hence nevessarily required, especially for glazed structures that could be subjected to extreme events (both natural hazards or human induced loads).

Given the increasing number of tragic attaks, in this context, several research studies have been carried out in the last years, to assess the performance of glass systems under explosions and high-strain impact. A recent state-of-the-art of research projects spent on glass windows and facades under extreme loads can be found in [4, 5]. Most of the literature studies include laboratory investigations on glass dynamic properties (i.e., to characterise the material performance under high strain events), analytical solutions for the analysis of the response of glass panes subjected to shock, advanced Finite Element (FE) numerical modelling of windows under the effects of air blast waves, as well as laboratory (or field) blast tests, aimed at assessing the performance of traditional glass windows and the feasibility / efficiency of possible mitigation solutions. It is in fact generally recognized that while glass windows and facades represent the first barrier for people from the environment (extreme events included), glass itself represents a vulnerable load-bearing component in buildings, and could be hence responsible of causalities, in the form of soft targets.

This paper aims at extending the current knowledge on the availability and reliability of design and analysis approaches for the vulnerability assessment of load-bearing glass structures. As such, the research study is focused on the an experimental and FE numerical investigation of an in-service glass footbridge. The case-study system is located in Aquileia (Italy), and was realized in the early 2000 within the religious context of the Roman Age, UNESCO Heritage Site, Basilica of Santa Maria Maggiore. Based on dynamic identification techniques, the actual state-of-the-art of the glass structure is assessed. It is hence shown, in particular, how non-destructive testing can provide useful feedback for the preservation and mitigation of glass structures and facilities.

3.2 Glass in Buildings

3.2.1 General Design Concepts

Generally speaking, glass structures are commonly complex systems, belonging and interacting to full three-dimensional buildings to which they have offer specific functions. At the same time, the glass structures themselves must act efficiently, as stand-alone load-bearing assemblies, so as to ensure appropriate resistance and deformation capacity, robustness, redundancy, etc. in their life-time [1, 6, 7]. As a result, they require specific design methods before their construction, but also optimal operational conditions, both under service loads and in presence of extreme design actions (including natural events, terroristic attacks, etc. [5, 8]).

While *fail-safe* structural performances should be conventionally maximized and accomplished with the support of existing design standards for buildings, however, the performance and mitigation of glass structures subjected to severe loading conditions still represents an open challenge and requires huge efforts. In most of the cases, no specific design regulations are available in guideline documents for constructions. In addition, the operational conditions that these structures have to suffer can be consistently different from the original design assumptions, hence resulting in potential unsafe performances and additional risk for the citizens.

3.2.2 Structural Design Requirements for Glass Roofs and Footbridges

Glass roofs and footbridges are strongly attractive for designers and have unevaluable aesthetic impact (see Fig. 3.1). In structural terms, these horizontal load-bearing systems must sustain pedestrians and offer appropriate resistance and stiffness, hence should be conventionally checked – in service loads – towards maximum deformations and stresses due to permanent and human induced live loads, see [6, 7]. Outdoor glass structures, in addition, may be asked to sustain snow and wind effects. In service conditions, finally, their vibrations should be also properly limited, being glass panels often characterized by high flexibility and small thickness-to-overall size ratios.

Even more restrictive design requirements are given by design standards for buildings under seismic actions, in terms of deformation capacity of the glazing components with respect to the other load-bearing elements. Such a kind of limitation requires, in most of the cases, a careful detailing of connections that should allow a certain movement accommodation, but at the same time preserve the redundancy of the system [9]. Special care is then also required for a reliable estimation of the dynamic characteristics for the glass assembly to verify [6, 7], including vibration frequencies, modal damping ratios, modal shapes.

3.2.3 Glass under Severe/Extreme Loads

According to the literature ([5, 11], etc.), and based on past observations from some tragic terroristic attacks, it is commonly recognized that glass shards and fragments are the major issue due to extreme design loads. In the past, they have been responsible of more than 60% of the casualties, see Fig. 3.2.

Structurally speaking, such an issue has been minimized for years via the so-called blast-resistant design approach, aiming at offering appropriate static/dynamic performances to facades, while preserving the integrity under shock [5, 10, 11]. The achievement of a similar performance requires, for traditional glass facades, specific knowledge of their static and dynamic features, being responsible of the overall response and possible local effects.


(a) (b)

Fig. 3.2 Examples of damaged glass facades after the tragic attacks at (a) Istanbul and (b) Brussels airports

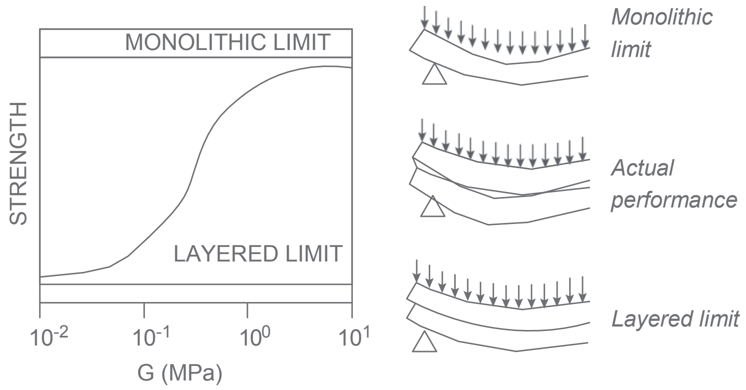


Fig. 3.3 Qualitative performance of a double LG panel in bending, as a function of the shear stiffness of the bonding interlayer. (Figure reproduced from Ref. [12] with the permission of Springer Nature, Copyright® License no. 4453711410573, October 2018)

Further critical configurations may derive, in glass structures in general, not only from extreme design actions, but also from ordinary operational conditions, hence careful attention is required through the full life-time of a given assembly. A combination of several aspects (including time, ambient and loading conditions) could in fact result – even in a limited period of time – in influencing parameters affecting the expected design performance of the glass structure.

Laminated glass (LG) systems, for example, are obtained by assembling multiple glass layers, bonded together via plastic layers ([1–3]). While Polyvinyl Butyral (PVB®) foils represent the conventional solution for glass sandwich sections, it is well-known that the mechanical properties of PVB (and others materials in use for glass applications [6, 7]) are susceptible to loading conditions. The actual structural response of a given LG member, as a result, is in most of the cases characterized by the presence of a relatively weak shear connection between the glass layers that hardly can offer a 'monolithic' performance (see Fig. 3.3).

As far as long-term loads, high temperatures or high relative humidity conditions, etc., are expected in the operational conditions of a given glass structure, as a result, a certain decrease of the shear modulus should be accounted for the bonding interlayers, with an appropriate analysis of the related structural effects. For most of the existing glass structures, however, the vulnerability analysis may result in uncertain predictions, and require advanced investigation approaches.

3.2.4 Non-destructive Methods for the Vulnerability Analysis of Glass Soft Targets

Within the design requirement of fail-sale performance goals, dynamic identification techniques and non-destructive testing could offer reliable and useful feedback, towards the assessment, preservation and enhancement of the structural performance of existing glass structures. According to the literature, no official definition exist for 'soft targets' [13, 14]. In terms of protection of citizens, however, the 'soft target' expression is mostly used to denote places with high concentration of people and low degree of security against possible attacks. The major distinction is made with respect to 'hard targets' – being representative of well-secured premises (i.e., government buildings, military premises, law enforcement offices, guarded non-governmental or commercial facilities, etc.). In other words, soft targets are vulnerable to attack and accessible to large numbers of people, such as sports venues, shopping venues, schools, transportation systems, religious facilities, open spaces, etc.

Given such a definition of soft targets, existing glass structures – due to their intrinsic vulnerability – can represent an additional source of risk for the citizens, requiring appropriate studies and possible structural health monitoring activities, so as to timely plan possible retrofit/mitigation interventions.

3.3 The Case-Study Glass Footbridge

In this paper, the dynamic performance of an existing glass suspension footbridge is preliminary analysed. The case-study structure is located in Italy, within the context of the Basilica of Aquileia (Udine). The Basilica includes the largest and one of the best preserved early Christian mosaics, and attracts over than 300,000 visitors every year. The glass footbridge object of study, in this regard, was realized in the early 2004, as a key strategy to preserve the roof mosaics and allow for their optimal visibility.

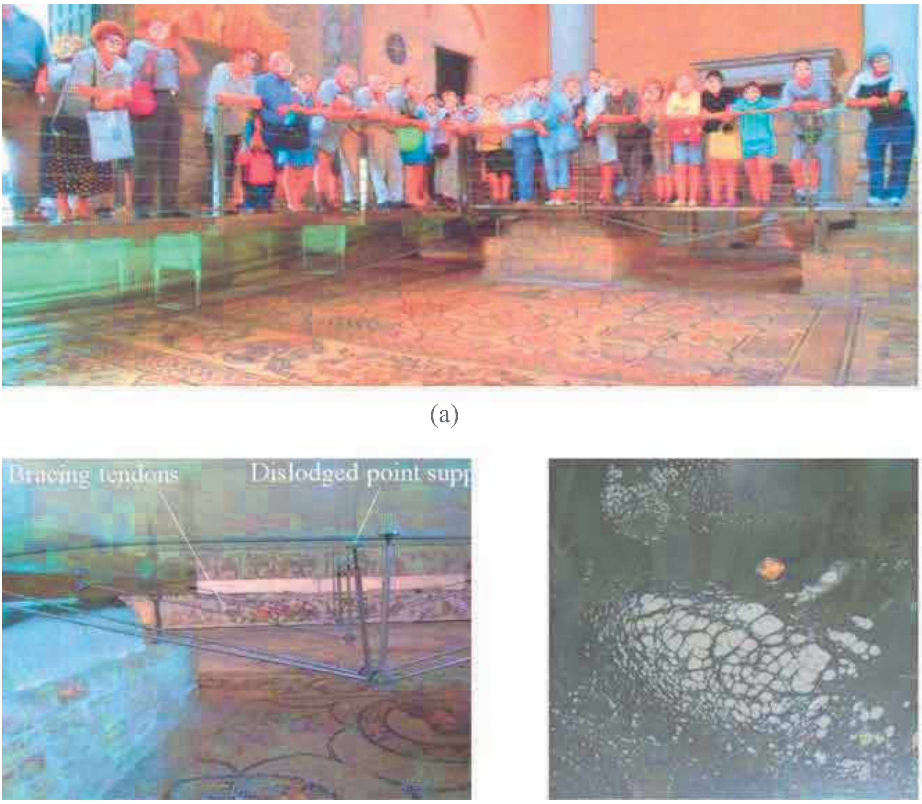
3.3.1 Geometrical and Mechanical Features of the Footbridge

The structural design of the glass footbridge was intended to maximize the transparency of the load-bearing components, and minimize their visual impact. To this aim, 118 LG panels were used (79 in the central nave of the Basilica, and 39 in the crypt). The overall footbridge was hence composed of a series of LG plates, steel frame members and suspension tendons supporting the LG components, with lateral steel-glass handrails (see Fig. 3.4).

According to the original design concept, each panel was designed as a triple LG section, via 3 fully tempered (FT) layers (12 mm thick/each) and 2 PVB foils (0.76 mm thick). An additional layer composed of annealed glass (AN, 6 mm its thickness) was positioned on the top of the LG panels, to preserve the integrity under cyclic anthropic loads (Fig. 3.5(a)). No mechanical connection was used for the LG-AN layers, with surface contact interactions only. A small, non-structural metal

(a) (b)

Fig. 3.4 The case-study glass suspension footbridge: (a) general view and (b) detail



(a)

(b) (c)

Fig. 3.5 Case-study glass footbridge: (a) live loads; (b) steel tendon and (c) local delamination frame was finally designed along the $B \times L$ edges of each LG panel, to keep the AN plates in position and preserve the LG sandwich integrity from humidity.

Globally, the so-assembled LG panels cover up to 140 square meters of walking surface, and have variable dimensions, from a minimum of 1.35 × 1.35 m (herein labelled as G1-type panels), up to 1.45 × 2.65 m (G2-type). While the G1-panels are point supported via a set of point mechanical supports (i.e., corner and mid-span steel restraints), major flexibility – and hence vulnerability and uncertainties – are associated to the bending performance of G2-panels, being supported along the short edges only (B ¼ 1.45 m, Fig. 3.4(b)) and spanning over $L = 2.65$ m. To limit the elastic deflections due to visitors, a bracing system was in fact originally designed, including pre-stressed steel tendons (10 mm the diameter, with three tendon pairs – 0.65 m spaced), and mid-span unilateral mechanical point supports, see Figs. 3.4 and 3.5.

3.3.2 Operational Conditions

After the construction of the footbridge, the structure was affected and still suffers for a combination of phenomena due to time, unfavorable ambient conditions (i.e., high humidity) and fatigue (i.e., continuous live loads due to visitors), see Fig. 3.5. For this reason, on-site vibration experiments were planned in 2017.

From a preliminary visual inspection of the glazed structure, for example, it was shown that:

- the tendons mid-span restraints – designed to half the span of G2-panels – proved to offer (in some cases only) a temporary/partial support for LG panels only, with local dislodgement of the unilateral supports (Fig. 3.5(b));
- the benefits of initial pre-stressing loads in the tendons were found to be mostly minimised by time effects; and
- partial surface abrasion and minor glass cracks, as well as condensation and debonding phenomena, were clearly observed for some of the LG panels (Fig. 3.5(c)).

3.3.3 On-site Vibration Experiments

The set of experiments was performed in November 2017, using the MEMS accelerometers prototyped in [15], see Fig. 3.6(a). Given the average size of G2-type panels, up to six MEMS sensors were used for each test repetition, and optimally positioned on the walking surface of the footbridge (i.e., #n sensors in Fig. 3.6(b)). Output-only experimental data were hence recorded (Fig. 3.6(c)). More details on experimental methods and assumptions within the campaign of dynamic testing can be found in [18, 19].

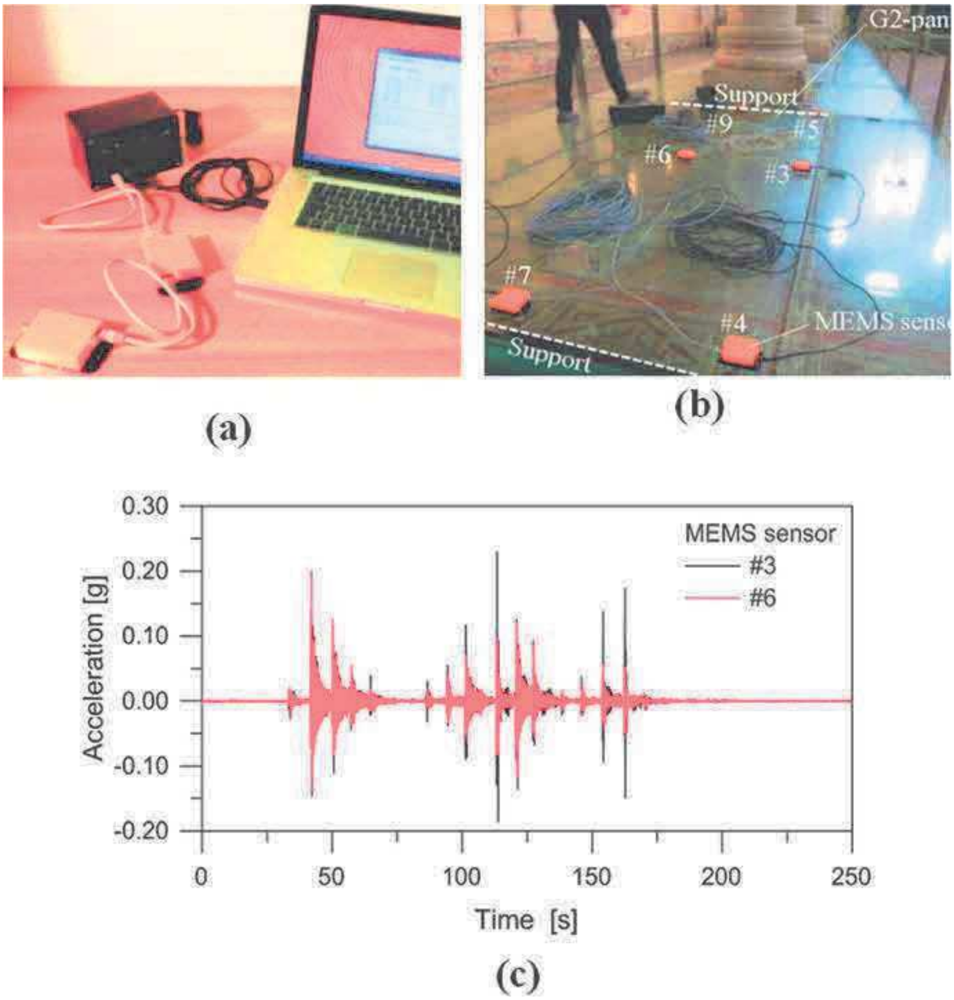


Fig. 3.6 Experimental modal analysis of the glass footbridge: (a) MEMS accelerometers; (b) test setup and (c) measurements

3.3.4 Finite-Element Numerical Modelling

A numerical investigation of the glass footbridge was then carried out in ABAQUS [16], to further explore the on-site experimental measurements (see Fig. 3.7). Special care was spent for the geometrical and mechanical description of the key structural components of the footbridge, as well as their reciprocal mechanical interaction under ordinary design loads. The typical FE numerical model herein discussed was described in ABAQUS to reproduce in detail the typical 1.45 × 2.65 m G2-panel, according to Fig. 3.7.

To this aim, 2D shell composite elements were used for the nominal LG section. Similarly, for the top AN layer, a shear flexible bond was defined on the upper face of the LG sandwich (E_{SOFT} ¼ 1 MPa its stiffness), so as to account for a contact

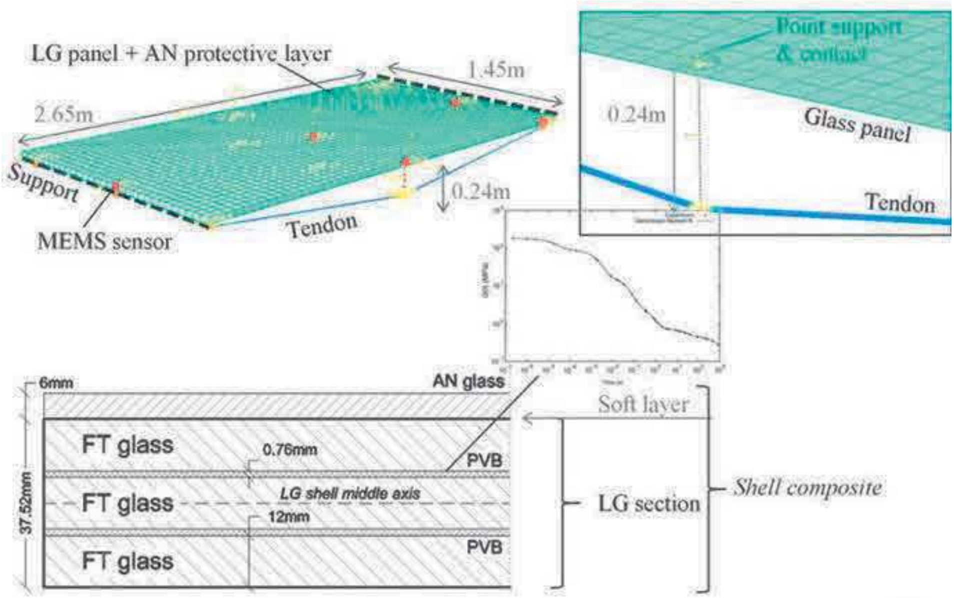


Fig. 3.7 Reference numerical model for the typical G2-panel (ABAQUS)

mechanical interaction. 1D beam elements were then used for the steel tendons (10 mm diameter). The MEMS sensors were described via lumped masses (0.15Kg/ each, Fig.3.7).

The so-defined structural components were supported to account for the actual restraints along B edges (i.e., Fig. 3.4(b)). A key role was indeed assigned to the mid-span steel point restraints, being responsible of the actual tendons-to-LG panels interaction. An unilateral point contact was hence defined, see Fig. 3.7, being able to react to compressive (vertical) loads only, while allowing free relative displacements/ rotations at the support-to-LG interface. In addition, based on the on-site visual inspection, pre-stressing loads in the tendons were fully disregarded.

The last uncertainty was represented by material properties. Nominal elastic features were reasonably considered for glass (E_{glass} ¼ 70GPa, ν_{glass} ¼ 0.23, ρ_{glass} ¼ 2500Kg/m^3) and steel (E_{steel} ¼ 160GPa, ν_{steel} ¼ 0.3, ρ_{steel} ¼ 7850Kg/m^3, with 1600 MPa the resistance at rupture), a tentative value was used for the shear stiffness of PVB (GPVB ¼ 8 MPa and E_{PVB} ¼ 24 MPa, with ν_{PVB} ¼ 0.49 and ρ_{PVB} ¼ 1100Kg/m^3). According to [1, 6, 7], such a stiffness is suitable for short-term loads (3 s) and room temperature (20°), but it is in contrast with the operational conditions of the case-study footbridge (see Fig. 3.5 and [6, 7]).

3.4 Summary of Experimental, Analytical and Numerical Results

3.4.1 On-site Vibration Experiments and Preliminary Analytical Estimations

The experimental records from MEMS sensors were accurately post-processed [17], to detect the fundamental mode of the footbridge (Fig. 3.6(b)). The selected LG panels, in particular, showed a beam-like flexural response, with $f_{TEST} = 14.97$ Hz the estimated fundamental frequency and $\xi_{TEST} = 1.20\%$ the corresponding modal damping.

In parallel, simplified analytical calculations were also carried out, for a further preliminary of the collected experimental data. More in detail, the first frequency of G2-panels was calculated as:

$$f_k = \omega_k / 2\pi \qquad (3.1)$$

where:

$$\omega_k = \left[\left(\frac{k\pi}{L} \right)^2 \sqrt{\frac{EI}{m}} \right] \qquad (3.2)$$

and $k = 1$.

In Eq. (3.2), m is the linear density of each beam-like panel, L the nominal span, E the longitudinal modulus of elasticity, I the flexural inertia of the resisting section. For simplified analytical estimations, a $t_{mono} = 3 \times 12 = 36$ mm thick, monolithic section was roughly considered, in place of the actual nominal LG + AN section (Fig. 3.7), with $E = E_{glass}$. The second moment of area I of the equivalent monolithic system was then estimated as:

$$I = B \cdot \left(t_{mono}^3 / 12 \right) = 5.63 \cdot 10^{-6} \text{ mm}^4 \qquad (3.3)$$

Following Eq. (3.1), a fundamental frequency $f_{AN} = 13.28$ Hz was hence calculated for the footbridge, with a scatter up to $\Delta_f = -11.2\%$ the exeperimental measurement, where:

$$\Delta_f = 100 \times (f - f_{TEST}) / f_{TEST} \qquad (3.4)$$

3.4.2 Finite-Element Numerical Simulations

Within the full FE study, parametric analyses were carried out to investigate the sensitivity of the fundamental dynamic characteristics of the footbridge to some key input parameters, such as the actual shear stiffness of PVB foils (Fig. 3.8), the size and pre-stress level of the bracing steel tendons, the LG-to-AN features, etc. Even in presence of markedly different input parameters and mechanical assumptions, the FE predictions resulted in a fundamental beam-like modal shape of G2-panels well agreeing with the vibration test measurements (Fig. 3.8(a)). Conversely, severe variations were observed in terms of fundamental frequency f_{FE}, see Fig. 3.8(b). There, the Δ_f scatter values are defined according to Eq. (3.4).

Worth of interest in Fig. 3.8(a) is that both the analytical and the corresponding monolithic FE model are not able to account for the actual bending stiffness/ restraints of the case-study footbridge (—11% the calculated frequency scatter). The bonding PVB foils proved in fact to have major effects on the dynamic parameters of the structure. Fine-tuning of FE dynamic predictions, in particular, resulted in an optimal E_{PVB} value in the order of =4 MPa, being well representative of time/ambient effects on the footbridge. Given the availability of such a reliable FE model for the existing structure, further detailed investigations will be planned in the future, so as to assess the actual vulnerability of the footbridge and its performance under possible extreme loading scenarios.

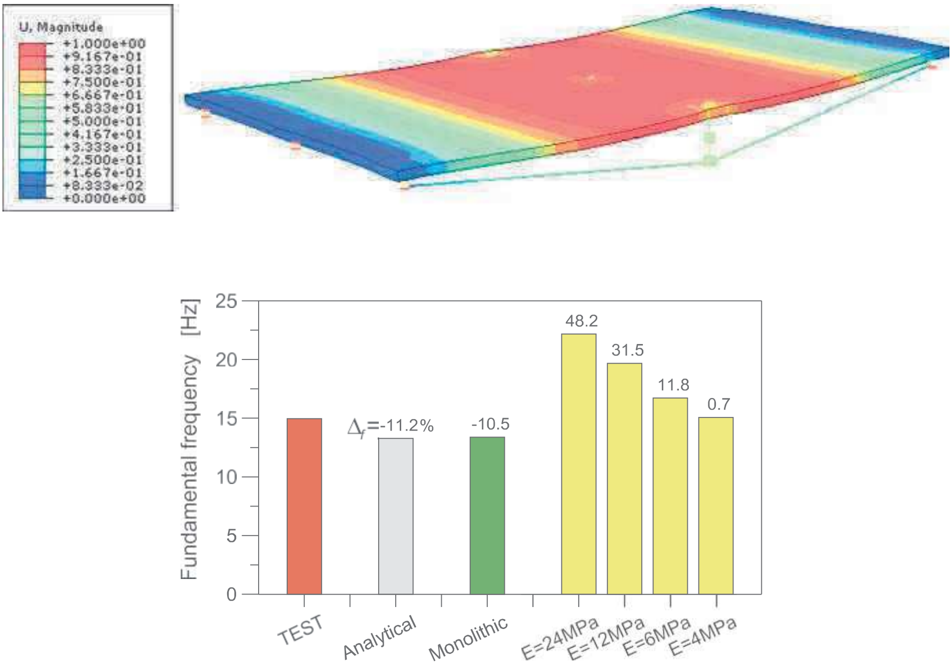


Fig. 3.8 Numerically predicted (a) fundamental modal shape and (b) frequency (ABAQUS)

3.5 Conclusions

In this paper, a preliminary dynamic characterisation of an existing glass suspension footbridge was presented, including on on-site vibration tests and numerical investigations. It was shown, in particular, that dynamic identification techniques can offer reliable feedback and support for the preservation, mitigation and enhancement of typically vulnerable structural systems. A combination of multiple aspects can markedly affect the modal estimations of the structure, hence requiring careful consideration towards *fail-safe* design performances. The post-processed data, in particular, confirmed the importance of non-destructive diagnostic investigations for retrofitting.

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