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Abstract	Load-bearing structural glass elements in buildings take often the form of columns, beams, plates and even stand-alone complex assemblies, where glass interacts with other constructional materials. Among others, the dynamic response o laminated glass (LG) elements attracts high interest, given that it relates to design of buildings under impact or seismic events. In this regard, a combination of various aspects should be properly taken into account for reliable estimates, such as the sensitivity of common interlayers to vibration frequency, ageing and operational conditions (for in-service systems). Further uncertainties for in-service LG members may regard the actual boundary condition, as well as the quantification of possible damage phenomena, like the presence of delamination, etc. These aspects are pointed out in the paper for a case-study in-service system.	
Keywords (separated by '-')	Laminated glass (LG) - Vibration frequency - Restraints - Field experiments - Analytical modelling - Finite Element (FE) numerical modelling	

Chapter 13
Vibration Analysis and Characterization of Damaged Structural Glass Elements

Chiara Bedon

Abstract Load-bearing structural glass elements in buildings take often the form of columns, beams, plates and even stand-alone complex assemblies, where glass interacts with other constructional materials. Among others, the dynamic response o laminated glass (LG) elements attracts high interest, given that it relates to design of buildings under impact or seismic events. In this regard, a combination of various aspects should be properly taken into account for reliable estimates, such as the sensitivity of common interlayers to vibration frequency, ageing and operational conditions (for in-service systems). Further uncertainties for in-service LG members may regard the actual boundary condition, as well as the quantification of possible damage phenomena, like the presence of delamination, etc. These aspects are pointed out in the paper for a case-study in-service system.

Keywords Laminated glass (LG) · Vibration frequency · Restraints · Field experiments · Analytical modelling · Finite Element (FE) numerical modelling

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13.1 Introduction

The design and structural performance assessment of laminated glass (LG) elements for building applications is a challenging task for designer and has an impact on the safety of customers. For such a kind of applications, the vibration and post-breakage residual stiffness and strength of LG components is of utmost importance (Fig. 13.1), especially in presence of extreme design actions [1].

From a practical point of view, the fractured (or post-breakage) performance of LG elements is a rather complex phenomena, given that it is characterized by the presence of glass fragments that are expected to adhere to the interlayer films [2]. This effect gives a certain residual structural capacity to the composite LG system, and this can be appreciated as far as the glass fragments are locked in place.

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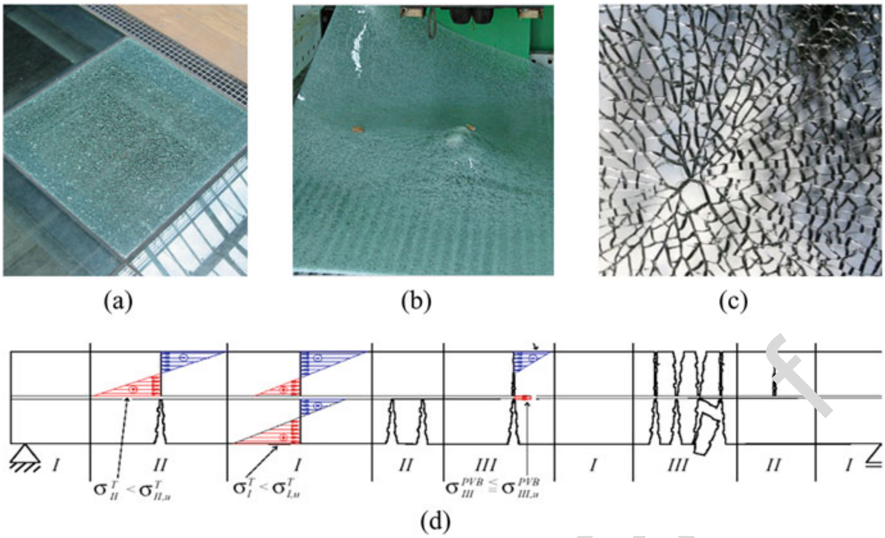

Fig. 13.1 Post-breakage performance of laminated glass (LG) members: (**a**–**c**) examples and (**d**) schematic representation of progressive fracture mechanisms in a double LG section, with evidence of stress distribution

Several aspects are however implicitly involved in the definition of key mechanical parameters that govern the complex post-breakage response of LG members (Fig. 13.1d), like the fragmentation of glass, the fragment size, the interlayer type, etc. [3].

In the present paper, the attention is focused on the analysis of in-service LG slabs and pedestrian elements that are expected to suffer for partial fracture and ordinary walking conditions [4]. In the framework of structural health monitoring approaches, the measure and analysis of vibration frequencies for various structural systems and facilities is typically associated to damage quantification and assessment [5]. For the examined LG slab elements, as shown, the mechanical and thus vibrational performances are expected to modify from the uncracked stage towards the post-breakage configuration, and potential risk may occur for customers [6].

To this aim, original experimental data are presented for an in-service glass walkway affected by glass fracture. The attention is focused on the fundamental frequency analysis, giving evidence of damage parameters and vibration effects [7, 8].

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13.2 Vibration Analysis of Structural Glass Elements

13.2.1 Regulations and Calculation Methods

The vibration serviceability assessment of a given load-bearing system is known to represent a strategic step of design [9, 10]. Besides the positive resistance and deflection verifications, a given system could be still weak in terms of comfort for the occupants, or even damage issues due to induced vibrations.

In the specific case of pedestrian systems composed of glass, the design challenge is even more complex rather than for slabs that are composed of traditional constructional materials. The structural mass, damping and stiffness are in fact key input parameters of the structure that are required to interact with a given moving load due to pedestrians.

While validated calculation methods are available since long in several technical documents and standards for the vibration serviceability analysis and assessment of concrete, steel, composite or timber slabs, this is not the case of structural glass solutions [11, 12]. Literature approaches are in fact intrinsically verified and calibrated for the analysis of horizontal load-bearing members in which the mass is expected to be typically higher than the occupants (depending on the final destination of the system). Further, the typical range of vibrations for concrete, steel or timber slabs is also well defined and can be predicted with the support of simple mechanical models.

The vibration analysis in structural glass slabs and roofs includes on the other side some additional uncertainties and difficulties for reliable calculations. First, the structural mass is often lower than the mass of the occupants. Such a primary effect involves a severe modification of the overall structural dynamic response of the system, with consequent variations in the conventional human-structure interaction phenomena. The fundamental vibrations of glass structures are consequently even more sensitive to the presence of standing or moving occupants. Finally, the vibration response of these systems is also affected by time and ambient conditions, given that the interlayers in use to bond the glass panels are subjected to a progressive degradation of stiffness that combines with a further stiffness modification in the same layers (as a direct effect of their viscoelastic nature and response to external induced vibration frequencies).

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13.2.2 Calculation Examples

Recent studies on the vibrational parameters and assessment of glass pedestrian systems can be found in [13, 14], where a case-study system has been investigated with the support of Operational Modal Analysis techniques, FE numerical models, and analytical models of literature that have been properly adapted to the explored in-service walkway of Fig. 13.2.

Fig. 13.2 Vibration analysis of an existing in-service glass walkway: (**a**) visual inspection and (**b**–**c**) details of the structural system. (Figures reproduced from [9] under the terms and conditions of the Creative Commons Attribution (CC BY) license)

The same case-study system was successively explored with a focus on point-fixed glass handrails schematized in Fig. 13.3 [15]. It was shown that the vibration analysis of in-service load-bearing members can find further uncertainties and complexities when the actual mechanical properties (i.e., shear rigidity of interlayers and supporting components [16]) may be difficult to quantify due to long-term and high-humidity phenomena, but also the real restraint effect of fasteners. In this sense, the use of experimental on-site techniques that are typical of the Operational Modal Analysis approaches can offer further support for diagnostics and assessment purposes in the post-breakage stage.

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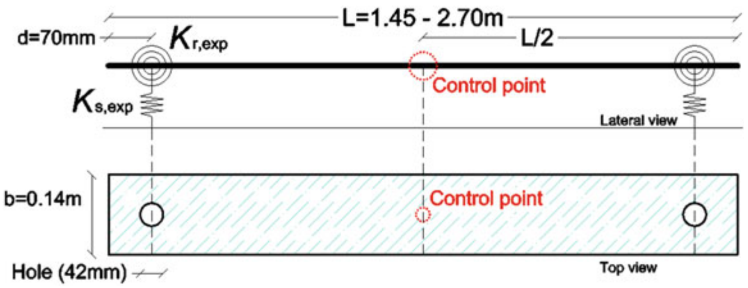

Fig. 13.3 Experimental LG specimens: schematic representation of the test setup. (Figures reproduced from [15] under the terms and conditions of the Creative Commons Attribution (CC BY) license)

(a) (b) (c)

Fig. 13.4 Case-study LG slab: (**a**) walkway (Crypt) and (**b**) reference LGU module, with (**c**) dimensions in m

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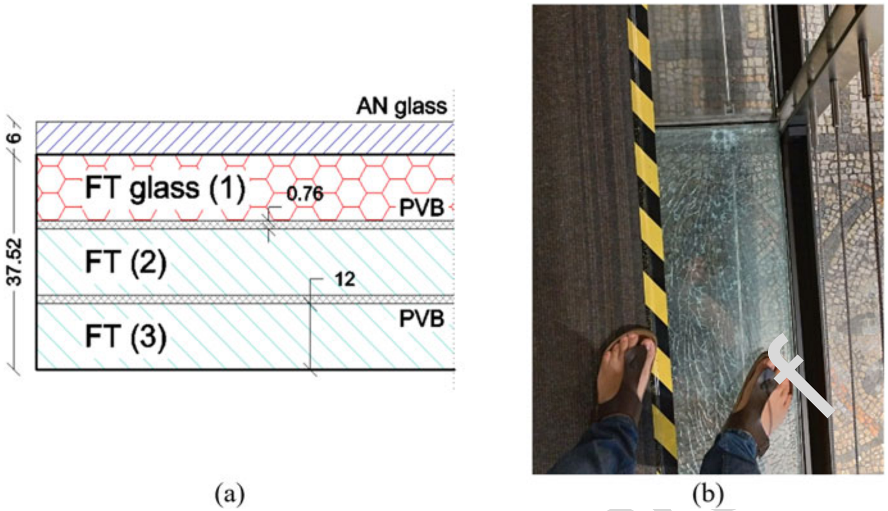
13.3 Post-breakage Vibration Analysis

13.3.1 Case-Study System

An original experimental program was carried out in August 2021. For the present study, the attention was focused on two original panels (from the set of 39 elements) that are currently part of the Crypt of Excavations suspension path (Fig. 13.4a).

The reference LG panel has a total dimension of 1.35 × 2.65 m (Figs. 13.4b, c). The slab consists of a triple section composed of fully tempered (FT) glass layers (3 × 12 mm the thickness) and interposed PVB foils (0.76 mm thick). An additional protective layer made of annealed (AN) glass (6 mm in thickness) is also positioned on the LG top surface (Fig. 13.5). The mechanical interaction between LG and the top AN layer was ensured by contact only.



(a)

(b)

Fig. 13.5 Case-study LG slab: (**a**) cross-section layout with dimensions in mm (in evidence, the fractured FT layer) and (**b**) views of LGF fractured module

The tested panels are supported along the short edges (Fig. 13.4c). To limit large bending deformations under walks, two pairs of pre-stressed tendons (10 mm the nominal diameter) composed of AISI 316 steel are used. Their mechanical interaction with glass is offered by unilateral mechanical mid-span point support only. The experimental investigation was focused on two selected modules of the walkway, being characterized by identical total dimensions as in Fig. 13.4c. The difference was represented by intact glass layers (LGU), or by the presence of one fractured glass layer for the LG section (LGF), as suggested by the preliminary observations summarized in Fig. 13.5. To note that the top LG layer was fractured during maintenance operations. A carpet was temporarily installed on the top layer, while waiting for the replacement of glass module. The fracture origin can be clearly seen in Fig. 13.5c.

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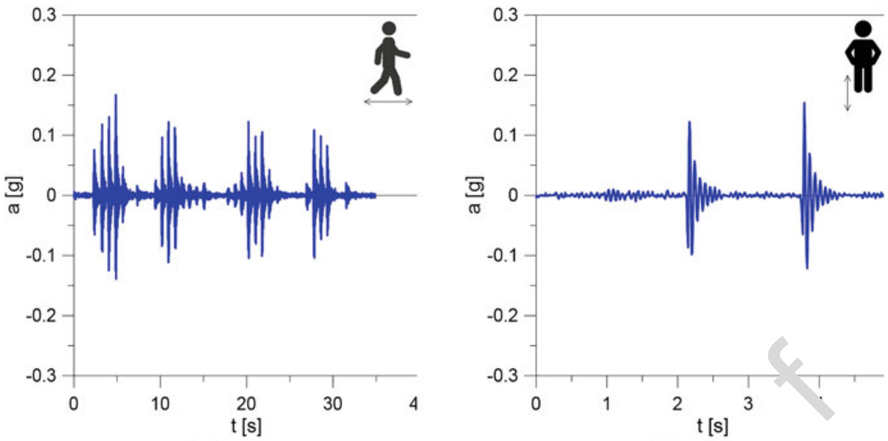
13.3.2 Test Setup, Instruments, Experimental Data

The experimental measurements were performed using tri-axial Micro Electro-Mechanical System (MEMS) accelerometers [17]. The experimental program was deliberately focused on LG modules of similar global dimensions and boundary conditions, so that a direct comparative analysis could be carried out.

In this context, the experimental measurements were collected for two LGU and LGF modules in Figs. 13.4 and 13.5. A single occupant was involved for measurements (M = 80 kg). Out-put-only tests data were collected under the effects of linear walks and in-place jumps (Fig. 13.6).



(a) (b)

Fig. 13.6 Example of vertical acceleration records under (**a**) linear walking path or (**b**) on-site jump of single occupant (detail)

The experimental analysis included different configurations/repetitions on the two tested modules (18 for LGF and 14 for LGU). A single MEMS sensor was repeatedly moved on the slab, so as to capture the acceleration time histories from control points #1 to #5 in Fig. 13.4c. The typical record was characterized by a maximum duration of ≈2 min.

13.3.3 Experimental Results

The experimental measurements were post-processed and analysed with the support of SMIT Toolsuite [18], in order to detect the fundamental vibration parameters of the structure object of study. The test setup and experimental protocol was optimized from [13, 14], where some LG modular units of the case-study walkway have been previously explored. The ERA-OKID-OO approach was used [19, 20].

A special care was paid for the analysis of vibration frequencies for the LGF modular unit compared to a similar LGU component (i.e., dimensions, layout and restraints) of the same walkway. For early damage detection and maintenance purposes, the frequency analysis represents in fact a first step that can reveal important modifications in the structural conditions and parameters of a given constructed facility. In this regard, frequency estimates alone cannot be expected to provide satisfactory outputs for complex comparative analyses, but may be optimized to quantify and detect potential risk and critical conditions.

The experimental records resulted in fundamental vibration frequencies in accordance with Fig. 13.7, where frequency estimates are proposed as a function of corresponding acceleration peaks (Fig. 13.7a) or in average values for the

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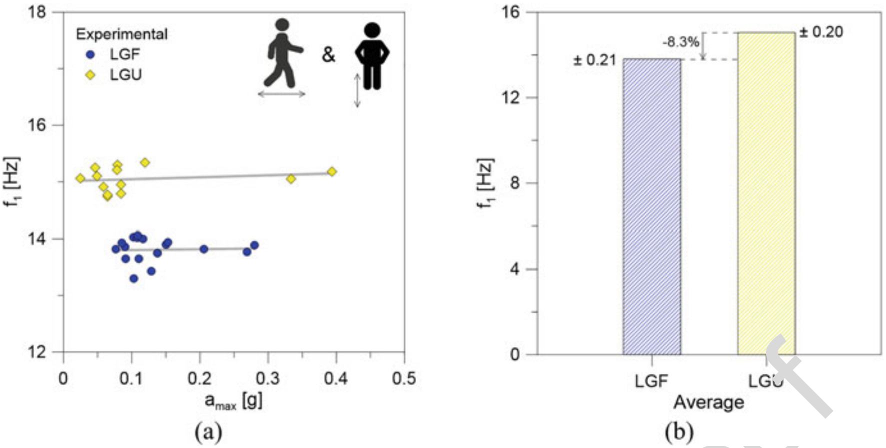

Fig. 13.7 Experimental fundamental frequency for LGU and LGF modules based on (**a**) vertical acceleration peaks or (**b**) average estimates.

investigated LGU and LGF modular units (Fig. 13.7b). Worth to note in Fig. 13.7a, for the explored acceleration range, is the higher sensitivity and lower vibration frequency of LGF estimates to various waking conditions, compared to LGU. The average frequency of LGF and LGU modules was calculated in 13.8 Hz (±0.21) and 15.05 Hz (±0.2) respectively. In this regard, it is clear that a direct comparison cannot be discussed for possible uncertainties in material properties or detailing. In any case, the experimental frequency scatter was quantified in around −8.3% decrease of frequency (and thus bending stiffness) for the LGF module (Fig. 13.7b), which could be representative of an approximate damage index for the walkway object of study.

13.4 Future Developments

The present experimental analysis proved that the actual operational conditions and mechanical properties have a crucial role on the vibration performance of structural glass elements.

In this regard, a key role is assigned to on-site experimental investigations and measurements that can support the detailed analysis of basic parameters and materials indicators.

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References

1. Bedon, C., Zhang, X., Santos, F., Honfi, D., Kozowski, M., Arrigoni, M., Figuli, L., Lange, D.: Performance of structural glass facades under extreme loads – Design methods, existing research, current issues and trends. Constr. Build. Mater. **163**, 921–937 (2018). https://doi.org/10.1016/j.conbuildmat.2017.12.153
2. Bitay, E., Tóth, L., Kovács, T.A., Nyikes Z., Gergely, A.L.: Experimental study on the influence of TiN/AlTiN PVD layer on the surface characteristics of hot work tool steel. Appl. Sci. Basel (2076-3417), 11–19 (2021). https://doi.org/10.3390/app11199309
3. Kott, A., Vogel, T.: Controlling the post-breakage behavior of laminated safety glass. In: Proceedings of the International Symposium on the Application of Architectural Glass, Munich (2004)
4. Tóth, L., Kovács, T.A., Nyikes, Z, Ghica, V.-G.: Increasing the H13 tool steel wear resistance by plasma nitriding and multilayer PVD coating. UPB Sci. Bull. B Chem. Mater. Sci. (1454-2331) **83**(2), 273–282 (2021)
5. Kovács, T.A., Mhatre, U. Nyikes, Z., Bitay, E.: Surface modification innovation for wear resistance increasing. IOP Conf. Ser. Mater. Sci. Eng. (1757-8981 1757-899X) **613,** 012039 (2019). https://doi.org/10.1088/1757-899X/613/1/012039
6. Kovács, T.A., Tóth, L., Nyikes, Z., Ghica, V.-G.: The analysis of microstructural changes depending on the electro-acoustic effect under the ultrasonic welding process of aluminum foils. UPB Sci. Bull. B Chem. Mater. Sci. (1454-2331) **82**(4), 213–222 (2020)
7. Nyikes, Z., Kovács, T.A., Tokody, D.: In situ testing of rail damages in accordance with Industry 4.0. J. Phys.-Conf. Ser. (1742-6588 1742-6596) **1045**, 1–6 (2018). https://doi.org/10.1088/1742-6596/1045/1/012032
8. Balázs, Á., Nyikes, Z., Kovács, T.A.: Building protection with composite materials application. Key Eng. Mater. (1013-9826 1662-9795) **755**, 286–291 (2017). https://doi.org/10.4028/www.scientific.net/KEM.755.286
9. EN 1990: Eurocode 0 – Basis of Structural Design – Annex A2: Application for Bridges. CEN, Brussels (2005)
10. ISO 10137: Bases for Design of Structures – Serviceability of Buildings and Walkways Against Vibrations, International Organization for Standardization (ISO), Geneva (2007)
11. Bedon, C., Fasan, M.: Reliability of field experiments, analytical methods and pedestrian's perception scales for the vibration serviceability assessment of an in-service glass walkway. Appl. Sci. **9**(9) (2019)
12. Bedon, C., Fasan, M.: "Correction: Bedon, C.; Fasan, M. Reliability of field experiments, analytical methods and pedestrian's perception scales for the vibration serviceability assessment of an in-service glass walkway. Appl. Sci. 2019, 9, 1936". Appl. Sci. **10**(3), 1032 (2020). https://doi.org/10.3390/app10031032
13. Bedon, C.: Diagnostic analysis and dynamic identification of a glass suspension footbridge via on-site vibration experiments and FE numerical modelling. Composite Struct. **216**, 366–378 (2019)
14. Bedon, C.: Experimental investigation on vibration sensitivity of an indoor glass footbridge to waling conditions. J. Build. Eng. **29**, 101195 (2020)
15. Bedon, C.: Issues on the vibration analysis of in-service laminated glass structures: analytical, experimental and numerical investigations on delaminated beams. Appl. Sci. **9**(18), 3928 (2019). https://doi.org/10.3390/app9183928
16. Bedon, C., Fasan, M., Amadio, C.: Vibration analysis and dynamic characterization of structural glass elements with different restraints based on operational modal analysis. Buildings. **9**(1), 13 (2019). https://doi.org/10.3390/buildings9010013

Uncorrected Proof

17. Bedon, C., Bergamo, E., Izzi, M., Noè, S.: Prototyping and validation of MEMS accelerometers for structural health monitoring – The case study of the Pietratagliata cable-stayed bridge. J. Sens. Actuator Netw. **7**, 18 (2018)
18. SMIT: Structural Modal Identification Toolsuite (2021)
19. Chang, M., Leonard, R.L., Pakzad, S.N.: SMIT user's guide
20. Chang, M., Pakzad, S.N.: Observer Kalman filter identification for output-only systems using interactive structural modal identification toolsuite. J. Bridge Eng. **19**, 04014002 (2014)

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