

MECHANICAL ENGINEERING THEORY AND APPLICATIONS



**RAUL DUARTE SALGUEIRAL GOMES CAMPILHO
KOUIDER MADANI
MOHAMED BELHOUARI**
EDITORS

FRACTURE MECHANICS

ADVANCES IN RESEARCH AND APPLICATIONS

NOVA

Complimentary Copy

Complimentary Copy

Mechanical Engineering Theory and Applications



No part of this digital document may be reproduced, stored in a retrieval system or transmitted in any form or by any means. The publisher has taken reasonable care in the preparation of this digital document, but makes no expressed or implied warranty of any kind and assumes no responsibility for any errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of information contained herein. This digital document is sold with the clear understanding that the publisher is not engaged in rendering legal, medical or any other professional services.

Complimentary Copy

Mechanical Engineering Theory and Applications

A Guide to Laser Welding

António Manuel de Bastos Pereira, PhD (Editor)

Eva Soledade Vaz Marques, MSc. (Editor)

Francisco José Gomes da Silva (Editor)

2024. ISBN: 979-8-88697-613-7 (Hardcover)

2024. ISBN: 979-8-89113-401-0 (eBook)

Case Studies in Computational Heat Transfer

Panagiotis (Takis) Sismanis.B.Eng, M.Eng, PhD (Editor)

2023. ISBN: 979-8-89113-300-6 (eBook)

Analytical Models of Thermal Stresses in Porous Two-Component Materials

Ladislav Ceniga (Editor)

2023. ISBN: 979-8-88697-113-2 (eBook)

Computer-Aided Design: Advances in Research and Applications

Dimitrios Tzetzis, PhD (Editor)

Panagiotis Kyratsis, PhD (Editor)

2023. ISBN: 979-8-88697-609-0 (Softcover)

2023. ISBN: 979-8-89113-147-7 (EPUB)

Mathematical Determination of Residual Stresses in Two-Component Materials

Ladislav Ceniga (Editor)

2022. ISBN: 979-8-88697-112-5 (eBook)

More information about this series can be found at

<https://novapublishers.com/product-category/series/mechanical-engineering-theory-and-applications/>

Complimentary Copy

Raul Duarte Salgueiral Gomes Campilho
Kouider Madani
and Mohamed Belhouari
Editors

Fracture Mechanics

Advances in Research and Applications



Complimentary Copy

Copyright © 2024 by Nova Science Publishers, Inc.

DOI: <https://doi.org/10.52305/BLXK3748>

All rights reserved. No part of this book may be reproduced, stored in a retrieval system or transmitted in any form or by any means: electronic, electrostatic, magnetic, tape, mechanical photocopying, recording or otherwise without the written permission of the Publisher.

We have partnered with Copyright Clearance Center to make it easy for you to obtain permissions to reuse content from this publication. Please visit copyright.com and search by Title, ISBN, or ISSN.

For further questions about using the service on copyright.com, please contact:

Copyright Clearance Center
Phone: +1-(978) 750-8400 Fax: +1-(978) 750-4470 E-mail: info@copyright.com

NOTICE TO THE READER

The Publisher has taken reasonable care in the preparation of this book but makes no expressed or implied warranty of any kind and assumes no responsibility for any errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of information contained in this book. The Publisher shall not be liable for any special, consequential, or exemplary damages resulting, in whole or in part, from the readers' use of, or reliance upon, this material. Any parts of this book based on government reports are so indicated and copyright is claimed for those parts to the extent applicable to compilations of such works.

Independent verification should be sought for any data, advice or recommendations contained in this book. In addition, no responsibility is assumed by the Publisher for any injury and/or damage to persons or property arising from any methods, products, instructions, ideas or otherwise contained in this publication.

This publication is designed to provide accurate and authoritative information with regards to the subject matter covered herein. It is sold with the clear understanding that the Publisher is not engaged in rendering legal or any other professional services. If legal or any other expert assistance is required, the services of a competent person should be sought. FROM A DECLARATION OF PARTICIPANTS JOINTLY ADOPTED BY A COMMITTEE OF THE AMERICAN BAR ASSOCIATION AND A COMMITTEE OF PUBLISHERS.

Library of Congress Cataloging-in-Publication Data

ISBN: 979-8-89113-590-1 (hardcover)

ISBN: 979-8-89113-643-4 (e-book)

Published by Nova Science Publishers, Inc. † New York

Complimentary Copy

Contents

Preface	ix
Chapter 1	Introduction to Fracture Mechanics	1
	R. D. S. G. Campilho, K. Madani and M. Belhouari	
Chapter 2	Interfacial Crack Turning in Bi-Crystals of Cubic Symmetry: A Three-Dimensional Stress Singularity Analysis	17
	Reaz A. Chaudhuri	
Chapter 3	Stress Effects on Precipitation Growth in Solid State Devices	57
	Xinyu Huang and Kenneth Reifsnider	
Chapter 4	Thermo-Mechanical Fracture Modeling Governed by Topological Derivatives	89
	M. Xavier and A. A. Novotny	
Chapter 5	Damage and Post-Fracture Characterization of Glass Structures: Summary of Background Theory, Design Concepts and Recent In-Field Experimental Evidence	107
	Chiara Bedon and Claudio Amadio	
Chapter 6	Determination of Notch Tip Plastic Zone Using Digital Image Correlation (DIC) Technique	131
	Bahador Bahrami, Hamed Kariminejad, Hossein Talebi and Majid R. Ayatollahi	

Chapter 7	Analysis of the Performance of the Composite Repair Patch for the Mechanical Resistance in Fatigue and in Tension of a Damaged Plate.....	155
	Kouider Madani, Safaa Chahrazed Djebbar, Houari Amin, Mohamed Belhouari, Xavier Feaugas and R. D. S. G. Campilho	
Chapter 8	Experimental and Numerical Studies of Bonded Repair of Notched Laminates Composites	195
	M. Belhouari, A. Benkheira, K. Madani, M. Elajrami, R. D. S. G. Campilho and X. L. Gong	
Chapter 9	Load-Carrying Capacity of Bolted Connections with Slotted-in Steel Plates in Squared and Round Timber.....	221
	P. Dobes and A. Lokaj	
Chapter 10	Impact of Adverse Conditions on the Fracture Behaviour of Carbon-Epoxy Laminates.....	239
	F. G. A. Silva, R. D. F. Moreira and M. F. S. F. de Moura	
Chapter 11	Determination of Residual Stresses in a Pressurized Thin Cylindrical Vessel Weakened by a Finite Line Crack.....	259
	Reaz A. Chaudhuri and Lutfi El-Gerwi	
Chapter 12	Study on Upgrading the Fatigue of Mechanical Systems Such as Dispensing Lever Established on Life-Stress Prototypes and Sample Size	289
	Seongwoo Woo, Dennis L. O’Neal, Yimer Mohammed Hassen and Gezae Mebrahtu	
Chapter 13	Strategies to Install Seismic Base Isolation in Construction in Terms of Fracture Mechanics.....	321
	J. Cici Jennifer Raj, M. Vinod Kumar, Mehmet Serkan Kirgiz and Raul D. S. G. Campilho	
Chapter 14	Seismic Isolation in Construction Using Rubber Bearings and Its Application for Saving Earthquake Fracture.....	343
	Cici Jennifer Raj J., Vinod M. Kumar, Mehmet Serkan Kirgiz and Raul D. S. G. Campilho	

Chapter 15	Technological Solutions to Save New, Existing, and Monument Buildings from Seismic Damages and Fracture	367
	Razan Alzein, M. Vinod Kumar, Mehmet Serkan Kirgiz and Raul D. S. G. Campilho	
About the Editors.....		403
Index	405

Chapter 5

Damage and Post-Fracture Characterization of Glass Structures: Summary of Background Theory, Design Concepts and Recent In-Field Experimental Evidence

Chiara Bedon*
and Claudio Amadio

University of Trieste, Department of Engineering and Architecture, Trieste, Italy

Abstract

The mechanical performance of glass structures and load-bearing elements attracts the attention of several research studies, especially for those unfavourable or extreme operational conditions which may include possible degradation or even damage scenarios, and thus potential risk for customers. Severe damage and fracture of glass material for construction applications are typically regarded as accidental conditions which should be properly taken into account in design. Based on simplified considerations, it is assumed that any residual mechanical contribution of glass fragments can be fully disregarded. Glass fracture is in fact a rather complex phenomenon to assess and characterize, especially for existing structures, due to the combination of a multitude of influencing variables and unknown parameters. Knowledge and early prediction of possible damage is thus of utmost importance for these brittle elastic load-bearing elements. At the same time, the mechanical characterization of damage parameters can facilitate possible robust diagnostics and residual capacity estimates. In this chapter, the potential

* Corresponding Author's Email: chiara.bedon@dia.units.it.

In: Fracture Mechanics

Editors: R. D. S. G. Campilho, K. Madani and M. Belhouari

ISBN: 979-8-89113-590-1

© 2024 Nova Science Publishers, Inc.

Complimentary Copy

and feasibility of in-field vibration frequency estimates, which are known to represent a preliminary but rather important diagnostic parameter for general constructional members, is verified for various glass elements in damage and post-fracture regime. Recent applications of non-destructive experimental methods and dynamic identification techniques are discussed.

Keywords: structural glass, post-fracture behaviour, fracture mechanics, design, experiments, modelling

Introduction

The mechanical analysis and performance assessment of load-bearing elements under ordinary or accidental and extreme design actions is a priority of designers, regardless the material in use and the structural typology. In this regard, a major effort is required when material degradation or even severe damage may be experienced during life-time interval (Haldimann, 2006; Udi et al., 2023). This condition may especially affect unconventional constructional materials, or assembled systems, or even sensitive material components which could reflect particular degradation as a function of operational conditions. Among others, laminated glass (LG) structural solutions, in which glass panels are bonded together by interposed films, may suffer (in terms of individual components as well as assembled sections) of different mechanical issues (Feldmann and Di Biase, 2018; CEN/TC 250, 2019a; CEN/TC 250, 2019b; CNR-DT 210/2013). This turns out – in case of improper design assumptions or maintenance interventions – in potential risk for customers, and in the need of specific efforts to address the problem (Bedon and Noè, 2021). For load-bearing elements with direct interaction with final users (like for pedestrian systems proposed in Figures 1 (a) and (b)), a reciprocal modification of mechanical and dynamic parameters should be properly taken into account in the early design process. As a major risk, glass fracture could initiate for a multitude of reasons, and have potentially catastrophic consequences for customers (Figure 1 (c)).

For glass systems under extreme design actions such as seismic events, explosions, impact or fire (Bedon et al., 2018), the load-bearing performance and post-fracture residual capacity assumes specific connotation which is strictly related to imposed loading, and could manifest in abrupt partial or total collapse of the system. In this chapter, major evidences are discussed for

simple glass elements under ordinary loads only. First, some basic concepts of material properties and fracture mechanics are recalled, followed by a summary of typical design assumptions for simple LG sections. Successively, some recent examples and applications are discussed, based on the use of vibration frequency estimates for the derivation of mechanical characteristics for LG elements with partial damage.

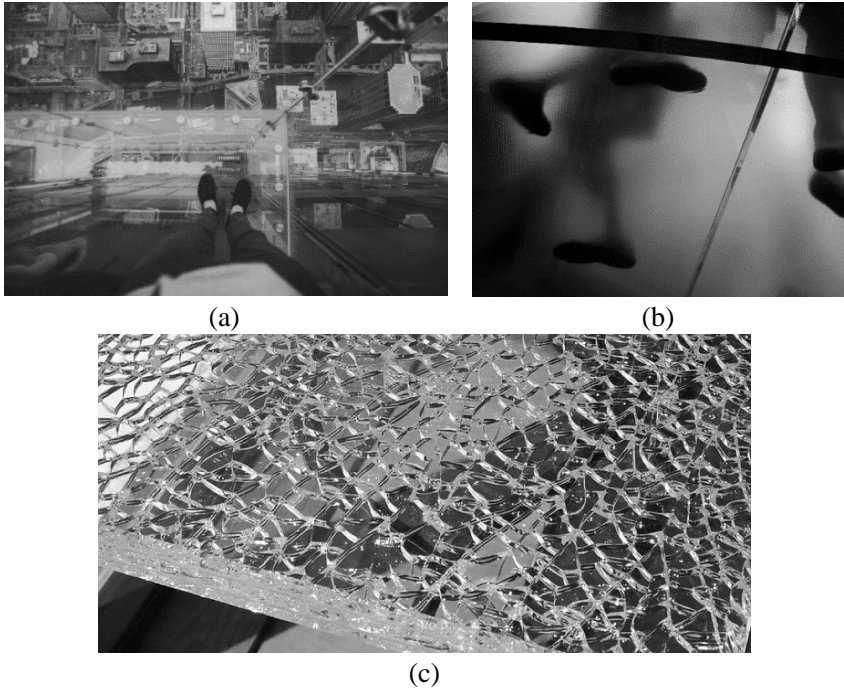


Figure 1. Examples of (a,b) glass pedestrian systems and (c) LG fracture (figures reproduced with permission from Unsplash).

Glass Structures

Material Properties and Their Effects on Mechanical Design

In the construction field, it is well recognized that glass material exhibits a substantially different mechanical response, compared to other consolidated and traditional materials in use for buildings and infrastructures like for example steel, aluminium, timber (Haldimann, 2006). Usually referred as

“brittle elastic” material in tension, glass is commonly associated to cracks which represent the most critical condition for structural design. Its lack of plastic residual performance makes glass generally unable to carry on mechanical loads after damage, and thus particularly unsafe, especially under certain boundary and loading conditions.

On the other side, cracks in tension for glass elements are quite different from classical brittle constructional materials like concrete, where – differing from glass – diffused micro-cracks propagate after damage and enable the anelastic mitigation of stress concentrations (CNR-DT 210/2013). All these intrinsic features require specific design assumptions but also maintenance and retrofit technologies, given that localized damage or local effects like stress concentrations around fractures, holes or areas of contact with other materials cannot be disregarded (Bedon et al., 2023b).

Glass material for applications in buildings is generally recognized to behave as a mechanically homogeneous, isotropic material, with linear-elastic behaviour until failure in tension and compression, but a typically pronounced brittle behaviour in tension (CNR-DT 210/2013). The latter, in terms of structural design, represents the most influencing parameter, given that the material load-bearing capacity is relatively low ($\approx 45 - 120$ MPa the characteristic value, depending on thermal treatment at the production stage) and possible fracture of glass can have major consequences with risks for customers.

Whilst the mechanical strength of glass under compression is generally much greater than in tension (i.e., in the order of 10 times), and for soda-lime silicate glass is estimated in the order (at the theoretical level) of 1000 MPa, this value represents an uncertain measurement, but suggests in any case design checks in the regions of maximum reaction forces and stress peaks. The increasing engineering knowledge of material properties (for glass and related materials), as well as the material response to various external conditions of loads and boundaries, facilitated the increasingly spread of load-bearing constructional members composed of structural glass. Nowadays, structural designers can thus take benefit of rather extensive design recommendations and prescriptions, which are developed on the base of robustness and redundancy concepts.

On the other side, several open questions still characterized the structural application and use of glass material in load-bearing components. In terms of design of new members, major uncertainties in terms of material scattered properties are often traduced in extremely conservative design concepts and

calculation procedures with heavy safety factors (Feldmann and Di Biase, 2018; CEN/TC 250, 2019a; CEN/TC 250, 2019b; CNR-DT 210/2013).

Additional questions affect also existing glass structures and components, which have been realized several years or even decades ago and currently suffer for time and other degradation phenomena (Bedon, 2019a; Bedon, 2020). In some cases, moreover, glass fracture could take place for several motivations, and severely affect the functionality and safety levels of structures (Figure 2).



Figure 2. Post-breakage stage for a 3-ply LG element in laboratory test setup.

Summary of Glass Fracture Mechanisms

The tensile strength of glass material is influenced by atmospheric humidity and also depends on stress amplification factors (microdefects) generally present on the surface as a result of the manufacturing and subsequent processes. As such, the strength of glass material must be evaluated in accordance with a fracture mechanics model like for example those for tensile strength that are available in the scientific literature (Load Duration Theory (Brown, 1972), Crack Growth Model (Evans, 1974), Glass Failure Prediction Model (Beason, 1980)). A common feature of these models is that they consider that the tensile strength of glass is associated with the propagation of a pre-existing dominant crack, and thus that its propagation is influenced by the duration of application of loads (Evans, 1974; Fischer-Cripps and Collins, 1995).

The strength of glass is determined by its high sensitivity to the presence of surface microdefects, and hence depends upon many factors (CNR-DT

210/2013). Microdefects, which are always present, may in fact increase over time under constant loads, leading to a deterioration in the mechanical performance of glass elements over time (this phenomenon is known as static fatigue). In addition, surface defects may increase and grow as a result of treatments such as abrasion, screen printing, enamelling, etc. Therefore, in the calibration of partial factors for the structural verification, variations in the intensity and duration of loads, finish conditions and ageing must be taken into account (Haldimann, 2006; Udi et al., 2023).

According to Figure 3, annealed, heat-strengthened and fully tempered glass elements have major differences in material strength and propagation of cracks in case of damage. The question is thus related to their residual mechanical contribution, once they are part of a composite LG section, and rather complex mechanisms take place between glass fragments, interlayers, and residual (still intact) LG components.

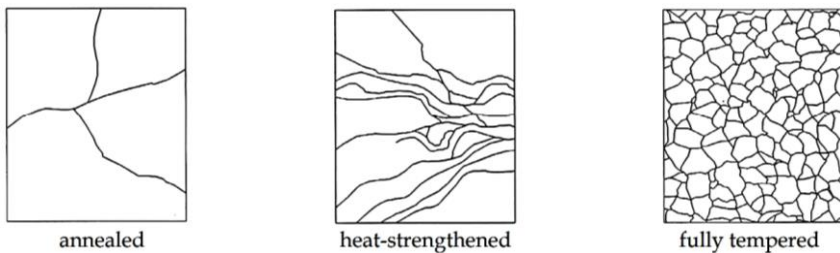


Figure 3. Schematic drawing of typical fracture patterns for annealed, heat-strengthened, and fully tempered glass types.

Structural Design of Simple Glass Elements

In the field of structural glass solutions for constructions, it is particularly advantageous to use at minimum double LG cross-sections for load-bearing elements like in Figure 4.

According to several technical standards for structural design (see for example (Feldmann and Di Biase, 2018; CEN/TC 250, 2019a; CEN/TC 250, 2019b; CNR-DT 210/2013) and others), a given LG member like in Figure 6 has a global capacity to sustain external loads which is intrinsically related to the actual stiffness of the composite resisting cross-section, and this strongly depends on the shear coupling effect of the bonding interlayer. To note that,

for calculation purposes, a rigid bond is taken into account at the glass-to-interlayer interface.

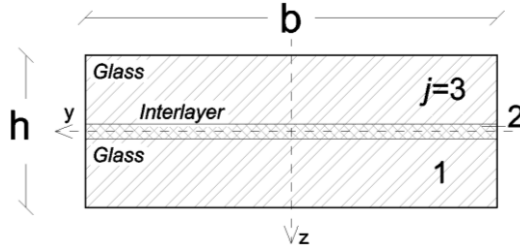


Figure 4. Example of 2-ply LG section with bonding interlayer.

For simplicity, the reference LG cross-section as in Figure 4 is taken into account in present considerations and assumed to be symmetrical, with a total thickness h composed of two glass layers (with thickness $h_1 = h_3$) and a middle bonding foil providing a certain shear coupling between them (with h_2 its thickness). The LG section has a total width b , and is typically used for load-bearing elements with L the span for beam-like or column-like setup, and even for plate-like configurations.

Glass material is characterized as linear elastic material with tensile brittle failure. Possible degradation of mechanical properties (Udi et al., 2023) are implicitly take into account. For conventional calculation assumptions in pre-failure stage (i.e., intact glass panels), it is assumed that $E_1 = E_3 = 70\text{GPa}$ is the nominal modulus of elasticity (MoE) of glass, with $\rho_1 = \rho_3 = 2500\text{ kg/m}^3$ the density and $\nu_1 = \nu_3 = 0.23$ the Poisson' ratio (EN 572-2:2004).

Disregarding the interlayer type and composition of typical use for structural glass, the bonding foil has generally a relatively low density ($\rho_2 \approx 1000\text{ kg/m}^3$). Most importantly, the interlayer is characterized by a viscoelastic behaviour, with relatively limited stiffness compared to glass (less than 1/3500 their ratio). Furthermore, this shear stiffness can suffer for major modification in mechanical properties due to a multitude of influencing (operational) and ageing (long-term phenomena) parameters.

On the other side, the interlayer itself has a key role for LG, given that it represents a smeared shear connection providing mechanical bonding to the composite LG section. It is thus the primary element responsible of the actual mechanical bond between glass layers, and thus composite bending stiffness against design loads, as well as stress distribution in the constituent layers (Figure 5).

Such a sensitivity of interlayers and its effects on the load-bearing performance of assembled LG sections can be efficiently taken into account in design considerations, for mechanical analysis purposes, based on simplified assumptions. However, the same verification procedure is based on conventional mechanical properties for materials and boundaries, and does not reflect the real aged scenario of the constructed LG system.

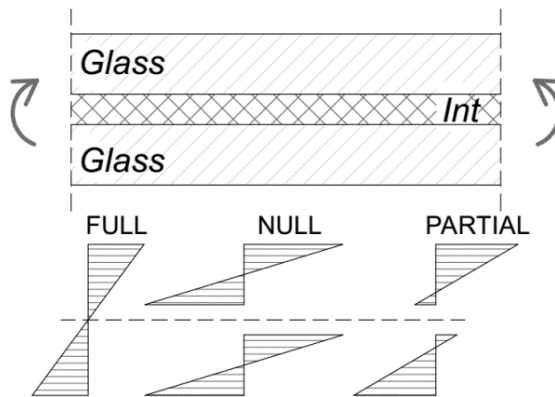


Figure 5. Qualitative example of stress distribution in a 2-ply LG section with rigid (“full”), weak (“null”) or intermediate (“partial”) shear connection offered by the bonding interlayer.

Design Strength Determination

For structural design calculations and stress or deflection verifications, linear elastic constitutive laws are assumed both for glass and interlayers. In the second case, the major attention is required for the calibration of elastic shear modulus to reproduce the most convenient condition of time-loading and temperature.

The calculation assumption in terms of glass material is that its modulus of elasticity (70 GPa the nominal value) is not sensitive to time and ageing effects, while the tensile strength of this brittle elastic material takes into account – among others – the effect of static fatigue phenomena, that is:

$$\sigma_g = f(k_{mod}) \quad (1)$$

with:

$$k_{mod} = 0.585 t_L^{-1/16} \quad (2)$$

and:

$$0.26 \leq k_{mod} \leq 1 \quad (3)$$

where t_L represents the duration of the load expressed in hours; $k_{mod}= 0.26$ is the minimum value for $t_L= 50$ years and $k_{mod}= 1$ for wind gust ($t_L= 3\text{-}5$ seconds).

In case of interlayers, the shear coupling for bonded glass panels is expressed as a function of the shear modulus G , which generally varies according to the service temperature, the duration of application of loads and ageing of the polymer. Conventionally, G is assumed to be constant and equal to the secant modulus for the characteristic duration of the applied loads. Typical values of technical interest for structural verifications can be found for example in (CNR-DT 210/2013).

Post-Fracture Modelling Strategies

For structural purposes, modelling strategies for the post-fracture response of LG elements can be able to capture local and global performance trends.

Successful examples can be found for example in (Baraldi et al., 2016; Biolzi et al., 2016; Biolzi and Simoncelli, 2022), where the progressive damage and post-fracture response of different LG systems and configurations has been investigated. For example, Discrete Element Modelling (DEM) strategies proved to represent a viable tool to predict the load–deflection curve from the cracking up to the collapse of LG members, and hence to efficiently assess the collapse limit states of structural glass.

In fact, DEM may simulate the non-linear composite behaviour that the polymeric interlayer and the glass fragments provide a member with, considering the crack patterns of the broken glass, the visco-elasticity of the interlayer, and the structural conditions of the member.

Combined Finite-Discrete Element Modelling (FDEM) approaches can be used, see Figure 6 (a) and (Lei et al., 2021), or even refined full three-dimensional based Finite Element models inclusive of cohesive interfaces among the bonded layers (Figure 6 (b) and (Beton et al., 2023a)).

On the other side, major issues and challenges are represented by the need of experimental tests to support the calibration of refined models, and thus on the difficult/uncertain application of these simulation strategies to existing LG structures, which indeed require a rapid quantitative measure of damage parameters and a mechanical detection of residual capacity potentials (Bedon et al., 2023b). Also, most of literature experiments on post-fracture performance assessment are limited to monotonic or few loading stages and does not account for the progressive interlock arrangement and mechanical degradation of glass fragments, which indeed can further severely reduce the residual stiffness under repeated vibrations (Bedon and Santos, 2023).

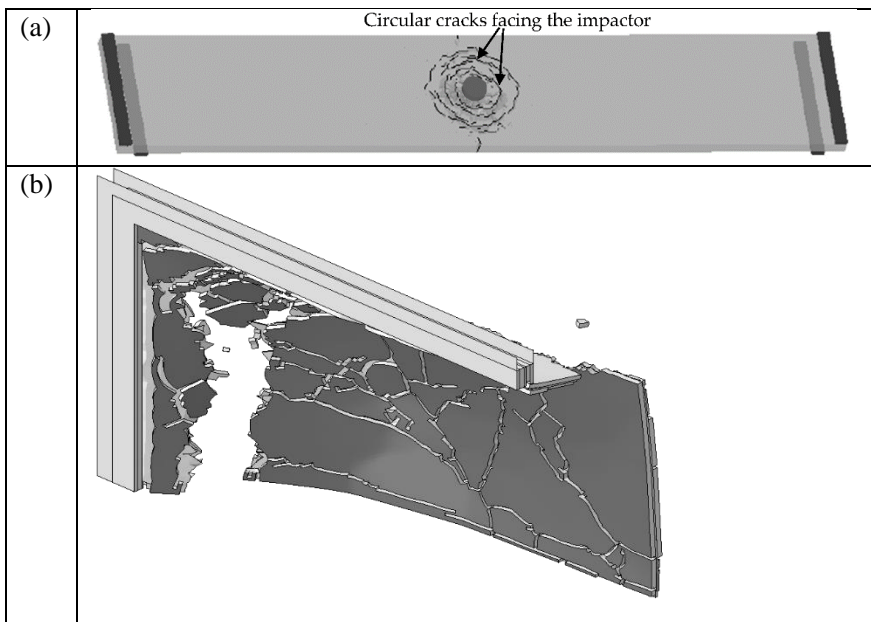


Figure 6. Examples of post-fracture numerical modelling strategies for LG elements. Figure (a) reproduced from (Lei et al., 2021) with permission under a CC-BY license agreement.

Role of Structural Health Monitoring and Recent Experimental Evidences

As far as a LG element/system with above features is taken into account, health monitoring needs can be rationally expected for in-service structures.

This is especially the case for load-bearing components characterized by a prevailing human-structure interaction (i.e., floors, partitions, balustrades, etc.), or even unfavourable operational conditions. As far as the attention is specifically focused on bonding interlayers only, literature evidences proved for example that discolouring of bonding foils can still represent an efficient “early warning” parameter for degradation detection (El-Sisi et al., 2022).

On the other side, discolouring itself is hardly quantifiable and possibly severe deterioration phenomena of mechanical features could have already taken place. In this context, more quantitative and reliable but at the same time practical and rapid strategies are needed for in-service glass structures (Bedon et al., 2023b). Most importantly, the experimental outputs should be able to easily support a structural health assessment of connections, and thus suggest possible maintenance and retrofit interventions, and minimize risk for customers. Overall, it is clear that the satisfaction of appropriate safety levels for in-service LG structures is necessarily correlated to a robust engineering knowledge of real-time performances and mechanical properties of stand-alone or assembled components (Figure 7). This is implicitly related to optimized functionality of mechanical components and maximized comfort for customers (i.e., especially for pedestrian systems). From a practical point of view, sensors have a primary role in a possible health monitoring protocol like in Figure 7.

Knowledge of the actual vibration frequency (Step 1 in Figure 7) represents a notoriously powerful indicator for structural diagnostics, but it is still limited in interpretation as single parameter. In any case, the experimental output from Step 1 needs a set of reference performance indicators for diagnostic purposes. A more refined analysis and post-processing elaboration of basic in-field experimental data is thus possibly represented by quantification of multiple health/damage parameters under real-time conditions (Step 2 in Figure 7). When conventional limits are known (i.e., as for design stage calculations), the experimental outputs from Step 2 can be addressed in terms of “residual capacity” for the system. An even more detailed interpretation of experimental outputs can be carried out with the support of dedicated FE numerical models, in order to characterize some basic equivalent material properties (Step 3 in Figure 7). This step is similarly powerful in outputs and uncertain in basic input parameters, especially boundaries and materials. Finally, in-service performance and even long-term effects for existing LG systems should be quantified in load-bearing functionality as in Step 4 of Figure 7.

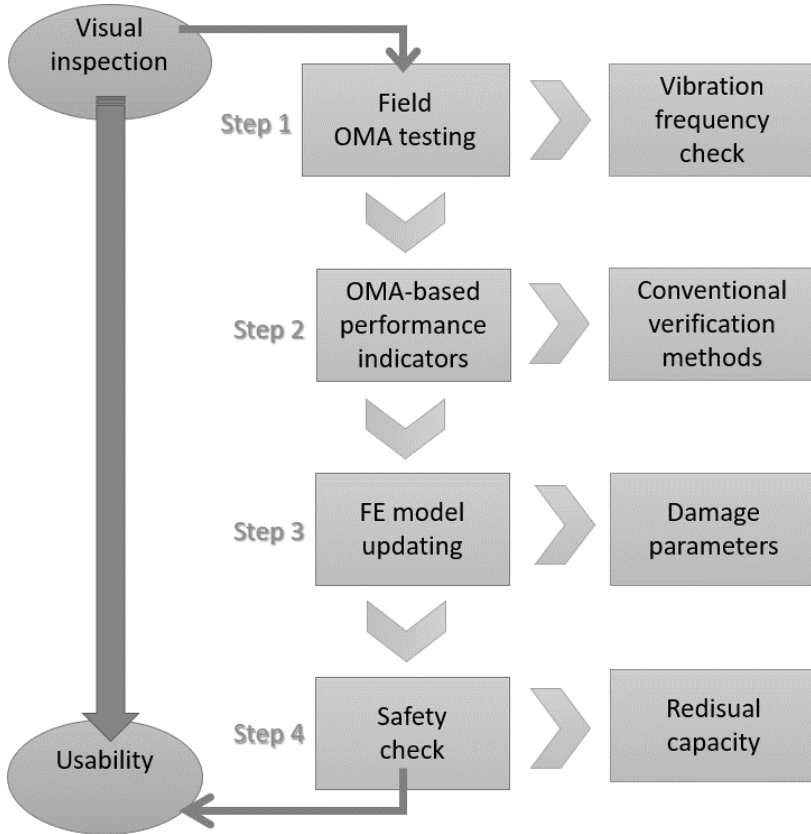


Figure 7. Possible procedural steps for safety assessment of in-service LG systems, based on sensors for health monitoring, as proposed in (Bedon et al., 2023b). Figure reproduced with permission under a CC-BY license agreement.

Recent in-Field Applications

As it happens for civil engineering applications and successful monitoring experiences based on classical inverse detection techniques, the use of Micro Electro-Mechanical System (MEMS) sensors looks promising also for special building applications characterized by a primary or prevailing use of LG components as load-bearing elements.

From a practical point of view, an efficient in-field analysis and diagnostics should be carried out in accordance with the key steps summarized in Figure 7. As far as a clear methodology with specific performance indicator

and limit values is available, several types of structural systems (with own composition, fixings and boundaries, loads, etc.) could be efficiently investigated like in Figure 7, including pedestrian structures (Bedon and Noè, 2021; Bedon, 2022; Bedon et al., 2023b), railings (Bedon, 2019b), facades (Bedon et al., 2018; Bedon et al., 2022), roofs, and general load-bearing components in which structural performances may require periodic of continuous monitoring interventions (see for example Figure 8).

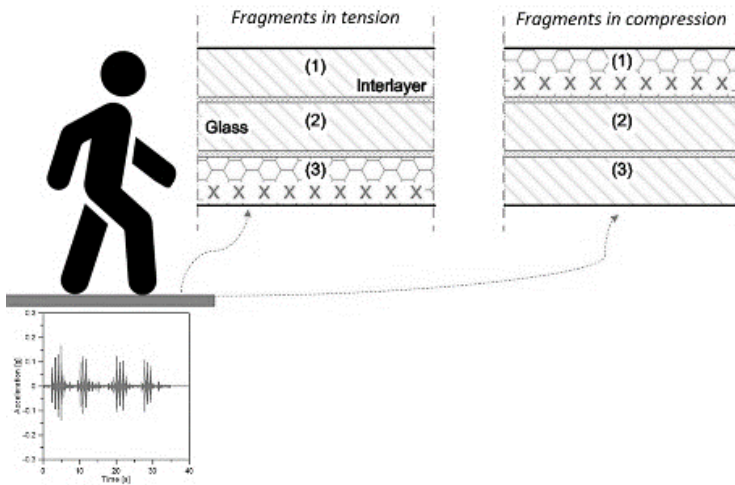


Figure 8. Experimental diagnostic analysis of an in-service LG pedestrian system with partial glass fracture.

In this regard, it is important to note that critical aspects for in-service glass systems in buildings are often represented by scarce knowledge on basic geometrical and mechanical properties of constituent materials, as well as on technical details about boundaries and restraints (Bedon et al., 2023b). This turns out in monitoring and diagnostic procedures for real LG applications in which uncertainties on several types of “connections” and details overlap. It could be thus particularly challenging to characterize a degradation of bonding interlayer connection with respect to actual connection of restraints, etc., and split these parameters from glass fracture itself.

In addition, lack of history details about operational conditions (such as temperature cycles, etc.) may represent an additional source of uncertainty for reliable analysis and quantification of residual mechanical and load-bearing capacities. In this sense, in-field experimental investigations should be possibly supported by technical documents about original projects, or further

integrated by dedicated iterative numerical calculations to parametrize the most influencing parameters and their effects on structural dynamic features which are object of experimental analysis. For newly realized LG systems, such a procedure could maximize the potential of the in-field experimental analysis by taking care of accurate characterization of a “time 0” description and identification of constructional behaviours and components. This reference configuration could be used to represent an efficient support for successive (periodic or continuous) in-field investigations during the nominal life of structure.

Glass Railings

Regarding the constituent materials for LG sections, it was previously recalled that glass in a minor part but especially the bonding interlayers are strongly sensitive to operational conditions and even ageing. The use of in-field MEMS sensors for monitoring purposes can be thus extremely efficient to capture any relevant modification in mechanical properties of the shear connection offered by interlayers in the composite LG section. Most importantly, the use of sensors acts in a more comprehensive way, given that it can support (as in Step 1 of Figure 7), the dynamic identification of the basic structural parameters, and thus the quantitative analysis of degradation phenomena (including both long-term or temperature/humidity sensitivity, and also possible delamination phenomena at the glass-to-interlayer interface like in Figure 9).

The experimental and numerical investigation proposed in (Bedon, 2019b) reports for example that point-fixing systems as in Figure 9 (b) can hardly match with ideal pinned and even clamped restraints. In this sense, in-field applications to which the present study is voted should be specifically investigated with attention to local and global effects of supports, even in the uncracked stage, to alert possible further damage propagation. At the same time, however, delamination as in Figure 9 can strongly affects the bonding connection due to interlayer between glass panels. To note that a single MEMS sensor was used in the experiments discussed in (Bedon, 2019b), to record tri-axial accelerations and inclinations under small-amplitude imposed vibrations for the examined LG members in beam-like setup.

The state-of-art experimental characterization of LG components necessitates consequently the support of analytical calculations (i.e., to detect the limit behaviour conditions), as well as simplified mechanical models as in Figure 10, and even more accurate numerical simulations.

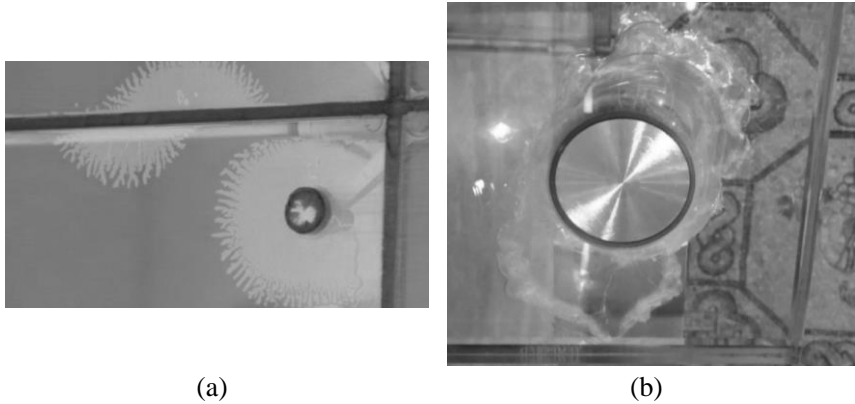


Figure 9. Examples of delamination phenomena in in-service LG systems. Figures reproduced from (Bedon, 2019b) under the terms and conditions of CC-BY license agreement.

There are in fact no doubts that soft gaskets and flexible components for restraints in LG systems can have major effects on the load-bearing and dynamic performance of even simple monolithic glass elements in buildings (Bedon et al., 2019). Typical effects can be efficiently quantified in terms of modification of vibration frequency but also damping parameters, which are of utmost importance for structural considerations (Bedon et al., 2019). In any case, practical empirical equations can be derived to predict the effect of partial flexibility in supports on the actual dynamic parameters of the glass components.

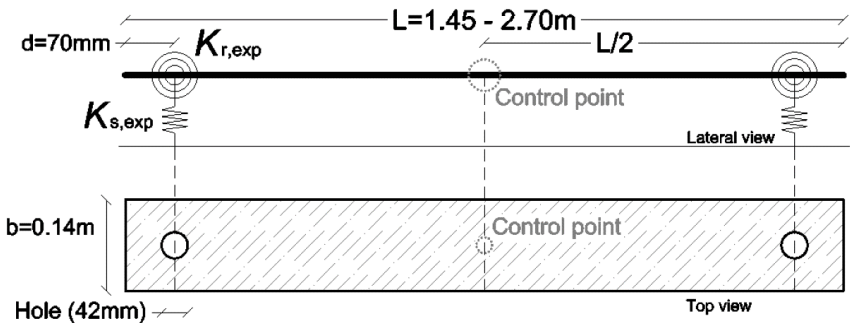


Figure 10. Reference experimental setup for the in-field investigation of 2-ply LG railings. Figures reproduced from (Bedon, 2019b) under the terms and conditions of CC-BY license agreement.

Glass Facades

Recent applications demonstrate that sensor-based investigations can be efficiently implemented for diagnostic purposes in (even ancient/historic) glass systems like facades, in which monolithic glass elements are often used in place of more recent LG solutions. Similar configurations may be particularly critical for safety of customers, given that they have been constructed without a specific design attention, and before any kind of technical regulations for glass structures was available.

A first criticality is thus represented by the use of monolithic glass which has no residual capacity after breakage. At the same time, these ancient systems are characterized by restraint connections which can be severely affected by uncertainties in mechanical capacities, as well as long-term degradation effects. The experimental and numerical study reported in (Bedon et al., 2022) for a historic facade system schematized in Figure 11, in this regard, showed that MEMS sensors combined with traditional dynamic identification techniques can offer a robust quantification of boundaries and overall dynamic performances.

To note that a single MEMS sensor was efficiently used to capture the most important features of a facade system with around 7 m of maximum size. The experimental analysis allowed to draw some important considerations about the limited structural capacity of the facade, with respect to present technical requirements in terms of load-bearing capacity under ordinary design loads and even seismic events.

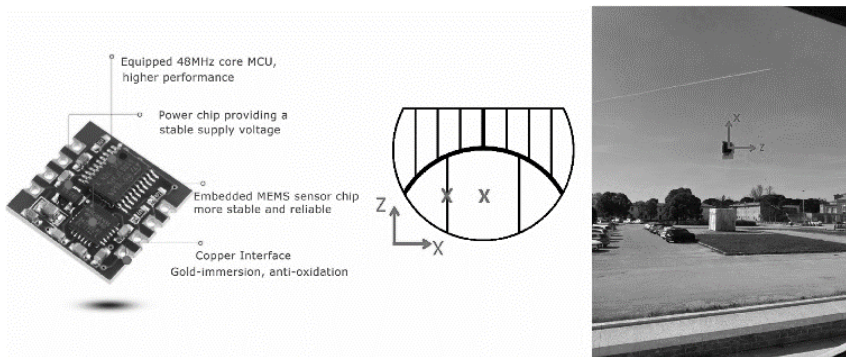


Figure 11. Experimental setup with single MEMS sensor for diagnostic investigations on a case-study historic glass facade with deteriorated glass-to-frame connections.

Glass Pedestrian Systems

More attention should be spent for LG systems like pedestrian structures (Bedon and Noè, 2021; Bedon, 2022; Bedon et al., 2023b), where possible material degradation, weak maintenance, unfavourable operational conditions, could take the form of possible risk for customers, see Figure 12 and (Bedon, 2019a; Bedon, 2020).

In this regard, an extended study was reported in (Bedon, 2019a; Bedon, 2020; Bedon, 2022; Bedon et al., 2023b) to quantify the actual mechanical performance and residual capacity for an in-service indoor walkway system as in Figure 12, characterized by severe ageing of constituent bonds (due to uncontrolled temperature and humidity conditions and a service life exceeding 15 years) but also to the presence of massive groups of visitors for the primary building, thus representing a continuous source of dynamic vertical load for the structural components.

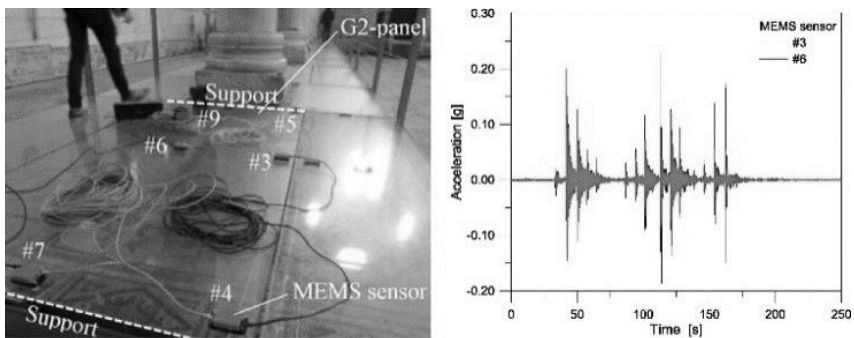


Figure 12. Experimental setup with multiple MEMS sensors for a pedestrian system made of LG components and corresponding records (example).

Most importantly, the in-field experimental analysis was further supported by dedicated numerical analyses, so that the actual state of connection in terms of interlayer bonding was properly quantified. This investigation step required parametric studies voted to make explicit the structural effects deriving from interlayer features, connection details, and even operational conditions (i.e., number of pedestrians, type of walking patterns, etc.). Additional investigations were exploited for the “empty” structural system, to focus on the load-bearing performance at the time of experiments, with respect to the “design” assumptions. It is thus important to note in Figure 13 that – for the LG system object of investigation – the bonding

level offered by interlayer was quantified in a degradation around -40% its original rigidity in “time 0” design conditions. Such an outcome is of primary need for safety assessment of in-service structures. Also, it further confirms the potential of sensor-based monitoring tools for characterization and maintenance of connections in LG structures.

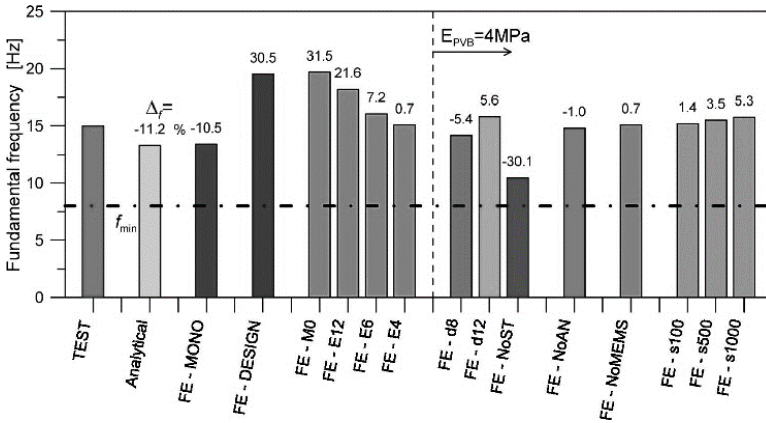


Figure 13. Parametric vibration frequency analysis for diagnostic investigation on a pedestrian LG system.

Glass fracture represents, in a possible sensitivity study like in Figure 13, a major uncertainty which involves a multitude of additional phenomena and reciprocally interacting effects. On one side, it is expected that glass fragments can contribute to residual stiffness as far as they are kept in position. Besides, this aspect also strongly depends on possible debonding, as well as on the loading setup, etc. The same case-study system discussed in Figures 12-13 was thus experimentally explored under an accidental scenario characterized by partial glass fracture for the resisting LG section, see Figure 14.

Behind the typical design assumptions, which disregard any kind of contribution from the cracked (or even sacrificial) glass layer, the experiments discussed in (Bedon and Noè, 2021) confirmed the complexity of post-fracture phenomena, but most importantly highlighted that in-field non-destructive methods can provide important performance parameters for damage quantification and residual capacity assessment. For the case-study system schematized in Figure 14, for example, the fundamental vibration frequency of the 3-ply LG section with partial glass fracture was quantified in an ≈ 8 -9% decrease compared to the intact LG configuration, which confirms the severity

of even partial glass fracture and the possibility of early warning damage predictions based on monitoring tools.

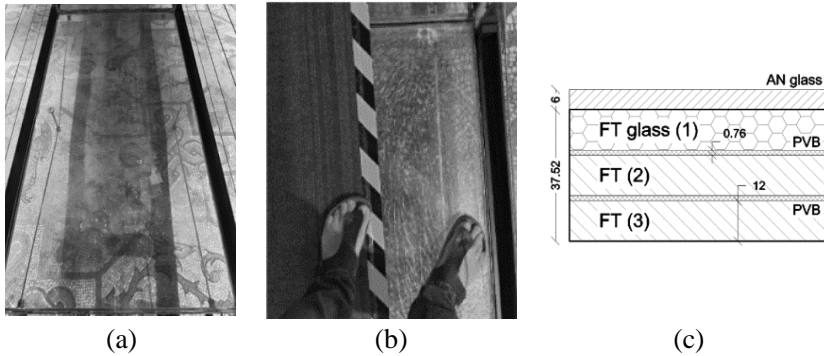


Figure 14. Experimental analysis of a case-study LG pedestrian system with partial glass fracture: (a) layout; (b) fracture detail and (c) schematic cross-section (measures in mm). Figures reproduced from (Bedon and Noè, 2021) under the terms and conditions of CC-BY license agreement.

Open Challenges and Preliminary Considerations

Behind the above evidences, the major gap to solve is that procedural methodologies and practical guidelines are not available for structural glass systems. As such, the use of monitoring or modelling strategies for damage and post-fracture mechanical characterization and assessment is – in most of cases – presently limited to few case-study examples that cannot be yet generalized. In the present chapter, for example, the attention was primarily given to in-field measurements and monitoring techniques in which the use of MEMS sensors has been minimized to optimize structural quantification and feedback. The selected recent in-field applications and examples of in-field glass structures proved the potential of methodology, but represent a first step to support future elaborations and generalized findings.

In this context, health monitoring needs and literature findings, as well as actual challenges for in-service LG structures, can be better understood as far as conventional design assumptions for structural verification of newly constructed elements and systems are taken into account, with respect to the real mechanical features and ageing effects of typical constituent materials.

Especially for in-service LG elements and structures, a detailed engineering knowledge of current mechanical properties and residual load-

bearing capacity levels is of utmost importance in building management. In terms of vibration assessment for in-service LG elements with degradation/damage, the recalled practical applications suggested for example that:

- The estimation of the fundamental vibration frequency is a first relevant but not exhaustive step for quantitative characterization of safety levels in existing glass structures. LG pedestrian systems are often characterized by relatively high fundamental frequency but often have relatively small mass compared to occupants;
- Fast, intermittent in-field experimental measures based on classical dynamic identification techniques could allow for the collection of a set of meaningful comparative data for an efficient check of mechanical features and modifications in a given existing structure. However, the experimental testing conditions should be possibly planned to reproduce the “normal” service configurations for the examined systems.
- For the proposed procedural steps and the methodology application to different LG systems, the in-field testing highlighted the need of a robust engineering knowledge for their interpretation, especially for generalized extensions.
- Due to intrinsic material properties and structural design assumptions, long-term phenomena and material degradation can induce severe modifications in time. After installation of LG elements and systems, it is hence important to monitor the evolution of basic parameters (and thus the residual capacity) over time.
- Overall, such a kind of intermittent diagnostic approach can facilitate the early detection of unfavourable configurations and hence promptly prevent maintenance interventions before any kind of severe damage could take place.

Conclusion

Glass structures and their mechanical performances in load-bearing applications are fascinating but equally challenging from a mechanical point of view, and thus attract and increasing attention from researchers, especially for those unfavourable or extreme operational conditions which may include

possible degradation or even damage scenarios, and thus potential risk for customers. Glass fracture, among others, is in fact a rather complex phenomenon to assess and characterize, especially for existing structures, due to the combination of a multitude of influencing variables and unknown parameters. Knowledge and early prediction of possible damage is thus of utmost importance for these brittle elastic load-bearing elements. In this chapter, some recent in-field experimental applications in which the potential and feasibility of monitoring protocols for damage mechanical characterization and early detection have been recalled, confirming the need of further efforts in this direction.

References

- Baraldi, D., Cecchi, A., Foraboschi, P. (2016). Broken tempered laminated glass: Non-linear discrete element modeling. *Composite Structures*, 140: 278-295. <https://doi.org/10.1016/j.compstruct.2015.12.050>.
- Beason, W. L. (1980). A failure prediction model for window glass. *NTIS* Accession no. PB81-148421, Texas Tech University, Institute for Disaster Research.
- Bedon, C. (2019a). Diagnostic analysis and dynamic identification of a glass suspension footbridge via on-site vibration experiments and FE numerical modelling. *Composite Structures*, 216: 366-378. <https://doi.org/10.1016/j.compstruct.2019.03.005>.
- Bedon, C. (2019b). Issues on the vibration analysis of in-service laminated glass structures: analytical, experimental and numerical investigations on delaminated beams. *Applied Sciences*, 9(18): 3928. <https://doi.org/10.3390/app9183928>.
- Bedon, C. (2020). Experimental investigation on vibration sensitivity of an indoor glass footbridge to walking conditions. *Journal of Building Engineering*, 29: 101195. <https://doi.org/10.1016/j.job.2020.101195>.
- Bedon, C. (2022). Time-domain numerical analysis of single pedestrian random walks on laminated glass slabs in pre- or post-breakage regime. *Engineering Structures*, 260: 114250. <https://doi.org/10.1016/j.engstruct.2022.114250>.
- Bedon, C., Noè, S. (2021). Post-Breakage Vibration Frequency Analysis of In-Service Pedestrian Laminated Glass Modular Units. *Vibration*, 4(4), 836-852. <https://doi.org/10.3390/vibration4040047>.
- Bedon, C., Santos, F. A. (2023). Effects of post-fracture repeated impacts and short-term temperature gradients on monolithic glass elements bonded by safety films. *Composite Structures*, 319: 117166. <https://doi.org/10.1016/j.compstruct.2023.117166>.
- Bedon, C., Fasan, M., Amadio, C. (2019). Vibration Analysis and Dynamic Characterization of Structural Glass Elements with Different Restraints Based on Operational Modal Analysis. *Buildings*, 9(1): 13. <https://doi.org/10.3390/buildings9010013>.

- Bedon, C., Markovic, D., Karlos, V., Larcher, M. (2023a). Numerical investigation of glass windows under near-field blast. *Coupled Systems Mechanics - An International Journal*, 12(2): 167-181. doi: 10.12989/csm.2023.12.2.16.
- Bedon, C., Noè, S., Fasan, M., Amadio, C. (2023b). Role of In-Field Experimental Diagnostic Analysis for the Derivation of Residual Capacity Indexes in Existing Pedestrian Glass Systems. *Buildings*, 13(3): 754. <https://doi.org/10.3390/buildings13030754>.
- Bedon, C., Santi, M. V., Fasan, M. (2022). Considerations on efficient procedural steps for seismic capacity assessment and diagnostics of historic structural glass systems. *Soil Dynamics and Earthquake Engineering*, 163: 107562. <https://doi.org/10.1016/j.soildyn.2022.107562>.
- Bedon, C., Zhang, X., Santos, F., Honfi, D., Kozłowski, M., Arrigoni, M., Figuli, L., Lange, D. (2018). Performance of structural glass facades under extreme loads - Design methods, existing research, current issues and trends. *Construction and Building Materials*, 163, 921-937. <https://doi.org/10.1016/j.conbuildmat.2017.12.153>.
- Biolzi, L., Orlando, M., Piscitelli, M. R., Spinelli, P. (2016). Static and dynamic response of progressively damaged ionoplast laminated glass beams. *Composite Structures*, 157: 337-347. <https://doi.org/10.1016/j.compstruct.2016.09.004>.
- Biolzi, L., Simoncelli, M. (2022) Overall response of 2-ply laminated glass plates under out-of-plane loading. *Engineering Structures*, 256: 113967. <https://doi.org/10.1016/j.engstruct.2022.113967>.
- Brown, W. G. (1972). A Load Duration Theory for Glass Design, Publication NRCC 12354.
- CEN/TC 250 (2019a). prCEN/TS xxxx-1: 2019—in-plane loaded glass components. European Committee for Standardization (CEN), Brussels, Belgium.
- CEN/TC 250 (2019b). prCEN/TS xxxx-2: 2019—out of-plane loaded glass components. European Committee for Standardization (CEN), Brussels, Belgium.
- CNR-DT 210/2013 (2013). Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Costruzioni con Elementi Strutturali in Vetro; National Research Council (CNR): Roma, Italy (in Italian).
- El-Sisi, A., Newberry, M., Knight, J., Salim, H., Nawar M. (2022). Static and high strain rate behavior of aged virgin PVB. *J Polym Res* 29: 39. <https://doi.org/10.1007/s10965-021-02876-5>.
- EN 572-2:2004. Glass in buildings - Basic soda lime silicate glass products. European Committee for Standardization (CEN), Brussels, Belgium.
- Evans, A. G. (1974). Slow crack growth in brittle materials under dynamic loading conditions. *Int. J. Fracture*, 10(2): 251–259.
- Feldmann, M., Di Biase, P. (2018). The CEN-TS “structural glass - design and construction rules” as pre-standard for the Eurocode. *ce/papers*, 2: 71.80. <https://doi.org/10.1002/cepa.911>.
- Fischer-Cripps, A. C., Collins, R. E. (1995). Architectural Glazings: Design Standards and Failure Models. *Building and Environment*, 30(1):29-40. [https://doi.org/10.1016/0360-1323\(94\)E0026-N](https://doi.org/10.1016/0360-1323(94)E0026-N).

- Haldimann, M. (2006). Fracture strength of structural glass elements – analytical and numerical modelling, testing and Design, Thesis n. 3671, EPFL Lausanne, Switzerland.
- Lei, Z., Rougier, E., Knight, E. E., Zang, M., Munjiza, A. (2021). Impact Fracture and Fragmentation of Glass via the 3D Combined Finite-Discrete Element Method. *Applied Sciences*, 11: 2484. <https://doi.org/10.3390/app11062484>.
- Udi, U. J., Yussof, M. M., Ayagi, K. M., Bedon, C., Kamarudin, M. K. (2023). Environmental degradation of structural glass systems: A review of experimental research and main influencing parameters. *Ain Shams Engineering Journal*, 14(5): 101970. <https://doi.org/10.1016/j.asej.2022.101970>.