18th European Conference on Earthquake Engineering

Shake-table prototype testing for sensor-based seismic damage assessment of non-structural elements

Marco Todaro[1], Mauricio Guamán[1], Davit Shahnazaryan[1], Daniele Sivori[1], Volkan Ozsarac[1], Gerard J. O'Reilly[1]

1- Centre for Training and Research on Reduction of Seismic Risk (ROSE Centre), Scuola Universitaria Superiore IUSS di Pavia, Pavia 27100, Italy

marco.todaro@iusspavia.it

Abstract

Current post-earthquake damage assessment of non-structural elements relies on manual inspections that are time-consuming and subjective to each surveyor's perception. The SONATA project addresses this limitation through the development of a full-scale prototype instrumented system, demonstrating the practical implementation of sensor-based technologies and data-driven procedures to support fragility and damage evaluations for non-structural elements. This paper describes the theoretical and practical considerations driving the design and assembly of a shake-table testing campaign being conducted at Eucentre's 9DLAB facility. The work focuses on constructing a test specimen prototype capable of tracking, through dense arrays of sensors and cameras, the dynamic behaviour of non-structural elements and their damage evolution during realistic earthquake loading. The key development aspects include comparative tests on specimens representing traditional Italian building components for commercial buildings (e.g., light partitions, suspended ceilings, mechanical equipment), a realistic setup replicating the actual boundary conditions and the cross-interactions between elements, the combined use of heterogeneous sensors to monitor global and local demands and response parameters, the use of advanced testing protocols to accurately reproduce seismic actions at different floors by exploiting the unique capabilities of 9DLAB in simulating relative motion between floors. By reproducing the actual conditions observed in real buildings during ground shaking and planning systematic comparisons between measured demands and observations of damage progression, the experimental campaign will form the basis to develop and update fragility curves and to test and automate the methodologies to assess damage to non-structural elements based on monitoring data.

Keywords: Experimental testing, Fragility functions, Non-structural elements, Bayesian updating, Shake table.

1- INTRODUCTION

Post-earthquake damage to non-structural elements (NSEs) has consistently dominated economic losses and downtime of buildings, as observed in Italy following the 2009 L'Aquila, 2012 Emilia-Romagna and 2016 Central Italy earthquake sequences, in which loss of functionality persisted well beyond the resolution of structural safety concerns [1, 2, 3, 4], as well as internationally following the 2011 Christchurch and recent Japanese earthquake sequences [5, 6], among others. Current practice still relies largely on manual field inspections: engineers visit each building, initially assess damage to the structure from outside and, if it can be safely inspected, document visible damage to structural components as observed inside the building and to NSEs, such as partitions, ceilings, cladding and mechanical equipment [7, 8]. This process is inherently slow and labour-intensive. Its reliability depends primarily on engineering judgment, access conditions of the building and safety of the technicians [7, 8] and its scalability breaks down when several buildings must be assessed within days of a major event [9]. The outcome is a systematic delay to informed decision-making on re-occupation, repair prioritisation, and resource allocation, negatively affecting the management of the post-earthquake emergency and recovery phases.

The SONATA project (Sensor-driven statistical tools to evaluate risks and manage safety in the built environment) addresses this gap by developing sensor-based technologies and data-driven procedures to automate NSE damage assessment and support rapid post-earthquake decision-making. The proposed shake-table campaign at Eucentre's 9DLAB facility imposes independent motions at two adjacent floor levels, measuring engineering demand parameters (EDPs) directly on each NSE through a comprehensive instrumentation layout. EDPs measured directly by sensor arrays, specifically peak storey drift (PSD) for drift-sensitive elements and peak floor acceleration (PFA) for acceleration-sensitive ones, are used to derive experimental fragility functions. Damage states (DS) are established by synchronising these measurements with artificial intelligence (AI) image recognition from cameras. These paired EDP and DS observations are then used to update existing analytical priors through Bayesian inference [10, 11], refining fragility estimates as experimental data accumulate. This integrated approach supports automated damage assessment for NSEs in monitored buildings. The experimental campaign will follow a two-phase structure: Phase 1 will test individual NSE typologies (partitions, ceilings, claddings etc.) under controlled boundary conditions to derive per-element fragility functions and build an image damage database for machine-learning model training; Phase 2 will test a full prototype room with several NSE categories co-installed to investigate interaction effects, update Phase 1 fragility functions under realistic seismic loading, and demonstrate the integrated SONATA methodology in realistic conditions. For this purpose, a numerical model has been developed for a case-study building, representing an 8-storey reinforced concrete (RC) moment-frame office building in L'Aquila and designed in accordance with Eurocode 8 [12] provisions. The numerical model is then used to determine the floor-level demands, which serve as input in the testing protocol.

This paper presents the design of the prototype testing campaign and its role within SONATA's broader sensor-based decision-support framework for NSEs. Section 2 outlines the methodology for EDP-based fragility and Bayesian updating. Section 3 describes the prototype design, 9DLAB configuration, instrumentation layout and testing protocol, while Section 4 discusses the expected outcomes in terms of NSE fragility functions, framework validation, and concluding remarks.

2- METHODOLOGY

The SONATA framework targets autonomous, sensor-based damage assessment of NSEs for monitored buildings: peak response quantities extracted from sensor recordings through signal post-processing are mapped through experimentally derived fragility functions to estimate damage state exceedance probabilities at building scale. DSs are inferred by an AI-based image recognition model, trained on damage observations from images acquired through cameras and drone surveys during the experimental campaign and supplemented by existing literature datasets. For each NSE category, a conditional probability of exceedance $P(DS \geq ds_i \mid EDP)$ is defined over the relevant demand range, where EDP is a scalar demand parameter characterising the demand imposed on the element at its bounding floor level, PSD for drift-sensitive elements and PFA for acceleration-sensitive ones [13]. The experimental campaign follows a two-phase structure designed to first build the tools required by the framework, then validate them under realistic conditions. Phase 1, illustrated in Figure 1, targets individual NSE categories under controlled boundary conditions.

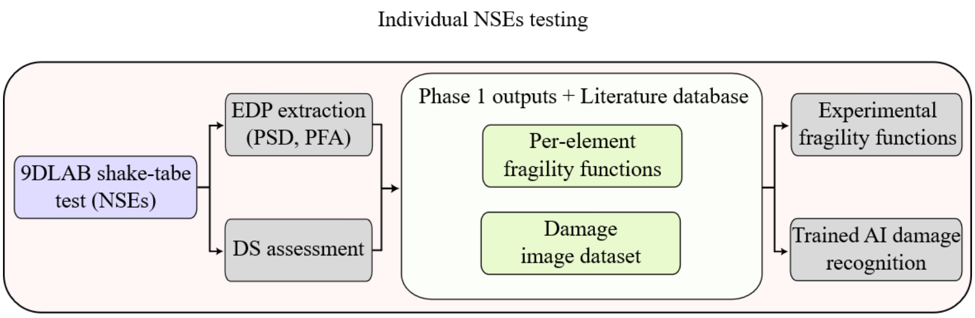

Figure 1- Phase 1 methodology workflow. Individual NSE shake-table tests extract EDPs and assess damage states, yielding experimental per-element fragility functions and a damage image dataset that, combined with literature databases, produce the analytical priors and the training data for the AI damage recognition model.

A series of amplitude-scaled runs produces paired EDP and DS observations used to derive per-element fragility functions. Shake-table campaigns are inherently resource-constrained: the number of test runs executable within a finite laboratory booking is insufficient, on its own, to estimate fragility model parameters with classical maximum-likelihood methods at acceptable confidence levels [10]. Analytical priors initialised from existing literature-based fragility functions for each NSE category [14, 15, 16, 17, 18, 19, 20] are therefore incorporated into the Bayesian estimates to compensate for the limited number of available test runs. Phase 1 also produces a set of damage images that, combined with larger publicly available datasets, constitute the training data for the machine-learning damage recognition model.

Phase 2, illustrated in Figure 2, shifts the focus from element-level fragility derivation to integrated system validation and rapid damage estimation, representing the core demonstration of the SONATA methodology under realistic conditions.

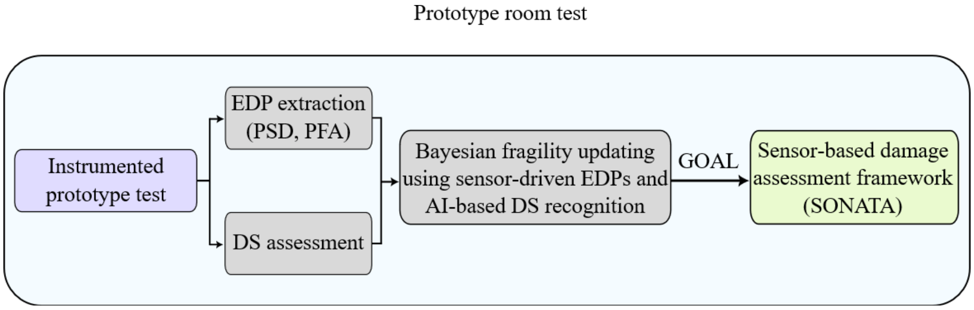

Figure 2- Phase 2 methodology workflow. A full-scale instrumented prototype with co-installed NSE categories demonstrates the integrated SONATA framework through Bayesian fragility updating using sensor-derived EDPs and the AI-based damage recognition model trained during Phase 1.

A full prototype room reproducing a representative office environment is assembled using the same NSE categories tested individually in Phase 1, with floor-level demand inputs derived from the case-study building model, generated with the SimDesign framework [21] for a site in the city of L'Aquila. This configuration reproduces the boundary conditions and element interactions found in actual buildings. DSs are established by synchronising peak response quantities from the sensor array with the AI-based image recognition model trained during Phase 1, demonstrating the automated damage assessment capability developed within SONATA. The resulting posterior fragility estimates propagate both modelling and experimental uncertainty in a formally consistent manner and support damage estimation at building scale.

3- EXPERIMENTAL CAMPAIGN DESIGN

This section describes the specimen design, test facility configuration, instrumentation, and testing protocol adopted for the experimental campaign. At the time of writing, the Phase 1 test series for gypsum partition systems has been completed at the 9DLAB facility, while the remaining tests on the other NSE categories are scheduled within the project timeline. The Phase 2 prototype test is planned for a later stage of the project.

3-1- PROTOTYPE BUILDING DESIGN

The reference prototype represents a room of an eight-storey RC moment-frame commercial office building designed for L'Aquila seismicity (soil class B, topography T1), with a regular 7 × 5 bay layout and a bay length of 5.0 m, as shown in Figure 3. The prototype room is 3.3 × 3.3 m in plan, consistent with the bay dimensions of the case-study building. For the shake-table implementation, a constant clear inter-storey height of 3.0 m is adopted, in line with contemporary Italian mid-rise office construction, where net clear storey heights typically range between 3.0 and 3.4 m once structural slabs and raised floor systems are accommodated. The prototype dimensions are therefore representative of the target building stock. Three NSE categories are targeted: interior partitions (glass and gypsum board), suspended ceilings (unbraced and braced), and pressurised piping systems. Together, these categories account for the majority of non-structural economic losses and post-earthquake business interruption in Italian commercial buildings [1, 13].

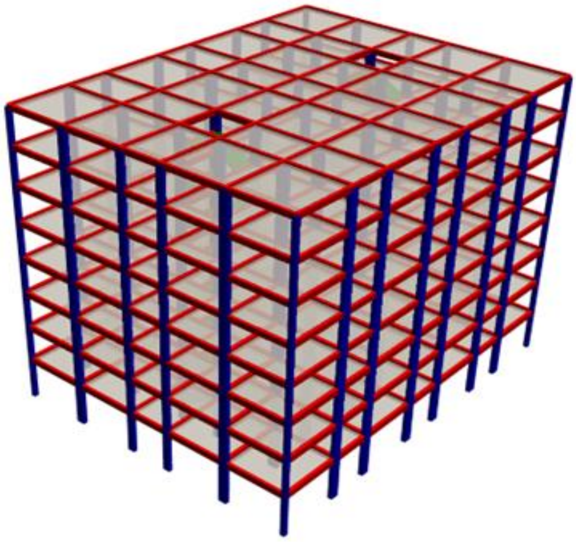

Figure 3- Case-study building adopted as the reference for prototype definition and floor-level demand derivation.

3-2- TEST SETUP AND FACILITY

The campaign is conducted at the 9DLAB facility at the Eucentre Foundation in Pavia, Italy. The system comprises two independently controlled shake tables, a lower and an upper platform, with an inter-table distance of 4.06 m. For this campaign, an upper timber frame and a lower steel support frame with floor system are installed to reduce the effective free height between the two platforms and align the test setup with the 3.0 m inter-storey height adopted for the prototype. The lower table plan is 4.80 × 4.80 m and the upper table plan is 5.00 × 7.00 m, with a peak horizontal velocity of 2 m/s at the base and 3 m/s at the upper table. The facility operates over a frequency range of 0.3-60 Hz. For EDP-relevant limits, the horizontal displacement capacity is ±1.0 m (2.0 m total) for both tables (PSD-related bound), and peak horizontal velocities are 2.0 m/s at the lower table and 3.0 m/s at the upper table (PFA-related bound). An overview of the 9DLAB shaking-table facility with the installed specimens is shown in Figure 4. A minimum operator clearance of approximately 0.5 m per side is maintained for installation and inspection access. Four corner regions and a 0.25 m perimeter strip are excluded from use due to actuator interference and anchorage boundary constraints. Figure 5 shows the specimen layout, in which both single-layer and double-layer gypsum partitions have been tested.

Figure 4- 9DLAB shaking-table facility at Eucentre with the gypsum partition specimens installed between the lower and upper tables.

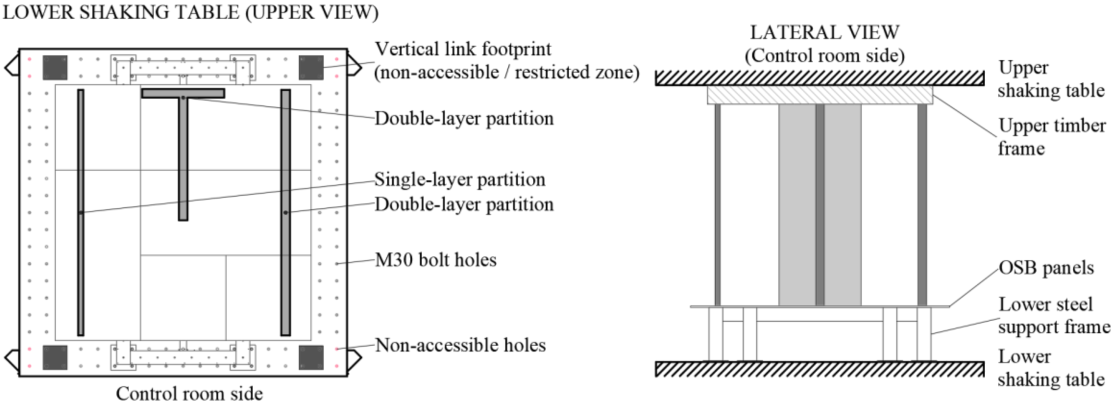

Figure 5- Specimen layout on the shaking tables: plan view of the lower table (left) and lateral view (right), showing the single-layer and double-layer gypsum partitions and the excluded boundary zones.

In single-table systems, reproducing the storey drift experienced by elements at different floor levels requires physically constructing the intermediate floor structure, including the load-bearing frame and its associated mass. The dual-table configuration of 9DLAB removes this constraint: the upper table directly imposes the prescribed floor-level motion at the top boundary of the prototype, allowing inter-storey drift to be reproduced without the need for an intermediate structural assembly.

3-3- INSTRUMENTATION AND DATA PROCESSING

Sensor deployment is designed to capture the EDPs required for fragility fitting while preserving unobstructed optical access to each element surface for post-run damage classification. Optical acquisition is provided through a combination of fixed laboratory cameras and repositionable tripod-mounted cameras, with unobstructed lines of sight to each NSE surface maintained to support high-resolution image and video capture during Phase 1 individual-element tests. This visual documentation supports post-run damage classification and AI model training. In the Phase 2 integrated prototype, the three-dimensional assembly of co-installed NSE categories limits optical access to individual element surfaces; AI-based damage recognition in this phase draws primarily on model weights trained and validated during Phase 1.

Mechanical sensing covers two physical quantities: acceleration and relative displacement. Acceleration sensors are deployed at multiple heights along the specimen to reconstruct floor-level and element-level acceleration demands, the primary EDP for acceleration-sensitive NSE categories. Displacement sensors measure relative motion between the lower table and the upper reaction frame, providing a direct experimental estimate of PSD, the governing EDP for drift-sensitive elements including partition systems [13].

A subset of cost-effective micro-electromechanical systems (MEMS)-based sensors is co-located with the laboratory-grade reference instrumentation at selected measurement points. This co-location enables direct benchmarking of cost-effective sensor accuracy and frequency response against a trusted reference channel under realistic seismic excitation. Acceptable performance of these devices in the frequency and amplitude range relevant to NSE response would support their deployment in permanent in-situ monitoring networks of the kind envisaged within the SONATA framework, where the practical constraints of building-scale installation preclude the use of laboratory-grade instrumentation.

Raw sensor recordings are processed in three stages to extract scalar EDP values. Time-history signals are first inspected for acquisition artefacts, baseline drift, and channel dropout, with affected channels corrected or flagged before further processing. Signals are then filtered in the frequency band relevant to NSE response, noting that building vibration of interest typically lies in the 1-10 Hz range for ambient response, with earthquake response extending to higher frequencies for local NSE modes. PSD and PFA are subsequently extracted for each run and assembled into the paired observation dataset used for Bayesian fragility updating, together with DSs established through post-run image and video review.

3-4- TESTING PROTOCOL

The seismic input to the 9DLAB system is delivered in acceleration control mode. Two independent input files, one for the lower table and one for the upper reaction frame, are prescribed simultaneously, directly reproducing the floor-level motions at two adjacent slabs. The input motions are derived from non-linear response-history analyses of the case-study building subjected to the 2009 L'Aquila Mw 6.1 earthquake recorded at the AQK station, retrieved from the European Strong Motion database. The record is applied at incrementally scaled amplitudes, with scaling factors (SFs) ranging from 0.3 to 4.0, and the resulting floor acceleration histories at the base and at the first floor, where the largest drift demands are expected, define the lower and upper table inputs, respectively. A bandpass filter between 0.25 and 50 Hz is applied to the signals to ensure compatibility with the shake-table requirements, and the amplitude of the transversal component is reduced at the two largest SFs to remain within the displacement capacity of the tables. Between seismic runs, low-amplitude white noise excitations are applied in each horizontal direction to track changes in the modal properties of NSEs as damage accumulates. At the end of the seismic sequence, low-frequency sinusoidal inputs of increasing amplitude are imposed to bring the specimens to more severe DSs.

The seismic hazard at the L'Aquila reference site is defined following NTC 2018 [22], assuming soil class B, topographic category T1, and a return period of 475 years (life-safety limit state, SLV), and the selected record is consistent with the corresponding target elastic response spectrum. The case-study building model, generated with the SimDesign framework [21], provides the non-linear response predictions from which the floor-level motions are extracted, and will similarly support preliminary verification of the prescribed table motions and estimation of expected NSE demands for the Phase 2 prototype test. The input floor acceleration time histories at the reference intensity and their 5% damped response spectra, compared with the target elastic response spectrum, are shown in Figure 6.

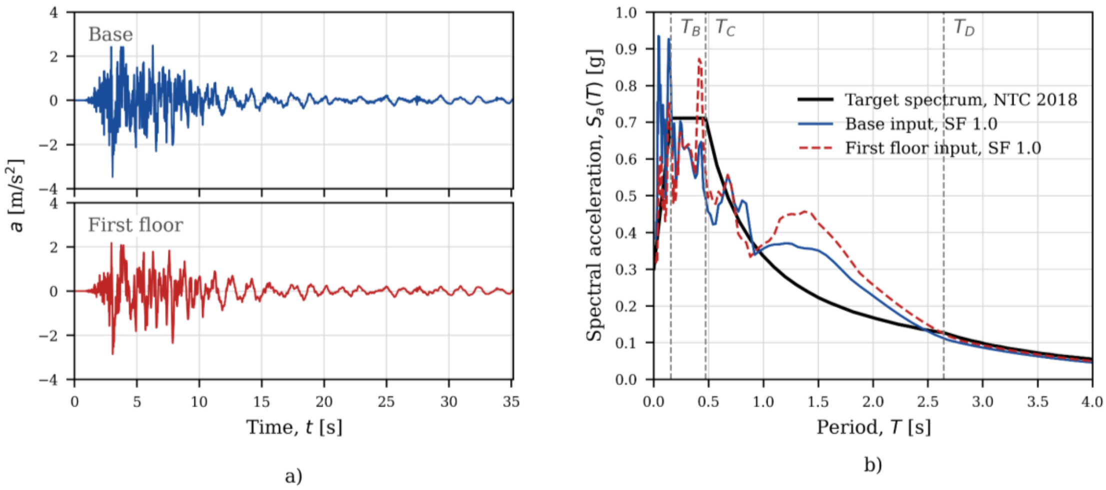

Figure 6- Input floor acceleration time histories at SF 1.0 (a) and corresponding 5% damped response spectra compared with the target elastic response spectrum (b).

Prior to the first seismic run, low-amplitude dynamic identification tests using white noise excitation are conducted on the fully assembled specimen to characterise the modal properties of NSEs and establish baseline sensor responses. These identification runs are repeated throughout the loading sequence to track changes in dynamic properties as damage accumulates.

4- SUMMARY

This paper described an experimental campaign to investigate the seismic behaviour of non-structural elements and how sensor outputs can be used to derive fragility and risk-based metrics. The campaign is designed to produce different types of output that together constitute the core deliverables of the SONATA project: experimentally grounded fragility functions for the targeted NSE categories, and a validated framework for sensor-based damage assessment for NSEs.

Phase 1 is expected to yield per-element experimental fragility functions for interior partitions (glass and gypsum board), suspended ceilings (unbraced and braced), and pressurised piping systems, expressed in terms of PSD for drift-sensitive elements and PFA for acceleration-sensitive ones. These functions are expected to offer a more representative characterisation of the targeted NSE categories under Italian commercial building conditions than currently available in the literature [14, 15, 16, 17, 18, 19, 20]. Phase 1 also produces a trained AI damage recognition model, validated against manually labelled observations from the same campaign, capable of automated and repeatable damage state classification for NSEs from image and video input.

Phase 2 is designed to validate the integrated operation of those two components under conditions representative of actual buildings. Successful completion of Phase 2 demonstrates that the framework is operationally viable and constitutes a direct evolution of the q-NAVI monitoring concept [23] toward autonomous, sensor-driven NSE damage assessment. In operational deployment, cost-effective MEMS-based sensor networks and co-located cameras replicate the measurement chain developed in the laboratory, enabling probabilistic damage estimation for NSEs without manual inspection. Where fixed cameras are not available, drone surveys can provide the image input required by the AI-based damage recognition model, replacing direct on-site image acquisition by technicians.

This paper has presented the design of a shake-table testing campaign conceived to advance sensor-based, automated damage assessment of NSEs beyond the current state of practice. The two-phase experimental structure, together with the integration of Bayesian updating and AI-assisted damage recognition, constitutes a scalable methodology for NSE damage estimation. When validated through Phase 2, this framework is intended to support rapid post-earthquake decision-making across monitored buildings, overcoming limitations of manual inspection demonstrated repeatedly following recent earthquake sequences.

5- ACKNOWLEDGMENT

The work presented here has been developed within the framework of the "Sensor-driven statistical tools to evaluate risks and manage safety in the built environment" (SONATA) project, which is a Starting Grant awarded by the Italian Science Fund (Fondo Italiano per la Scienza) at IUSS Pavia under grant number FIS2023-03215.

6- REFERENCES

[1] Earthquake Engineering Research Institute. The Mw 6.3 Abruzzo, Italy, earthquake of April 6, 2009. Eeri special earthquake report, EERI, June 2009. https://www.reluis.it/doc/pdf/Aquila/EERI_L_Aquila_report.pdf

[2] Rossi, L., Parisi, D., Casari, C., Montanari, L., Ruggieri, G., Holtschoppen, B. and Butenweg, C. (2019), Empirical Data about Direct Economic Consequences of Emilia-Romagna 2012 Earthquake on Long-Span-Beam Buildings. Earthquake Spectra, 35: 1979-2001. https://doi.org/10.1193/100118EQS224DP

[3] Braga, F., Manfredi, V., Masi, A. et al. Performance of non-structural elements in RC buildings during the L'Aquila, 2009 earthquake. Bull Earthquake Eng 9, 307–324 (2011). https://doi.org/10.1007/s10518-010-9205-7

[4] Perrone, D., Calvi, P.M., Nascimbene, R. et al. Seismic performance of non-structural elements during the 2016 Central Italy earthquake. Bull Earthquake Eng 17, 5655–5677 (2019). https://doi.org/10.1007/s10518-018-0361-5

[5] Baird, A., Tasligedik, A.S., Palermo, A. and Pampanin, S. (2014), Seismic Performance of Vertical Nonstructural Components in the 22 February 2011 Christchurch Earthquake. Earthquake Spectra, 30: 401-425. https://doi.org/10.1193/031013EQS067M

[6] O'Reilly GJ, Hasegawa K, Shahnazaryan D, et al. On the fragility of non-structural elements in loss and recovery: Field observations from Japan. Earthquake Engng Struct Dyn. 2024;53:1125–1144. https://doi.org/10.1002/eqe.4066

[7] Editor. (1998). Post-earthquake building safety evaluation procedures : Preparedness checklist and response plan for territorial authorities . Bulletin of the New Zealand Society for Earthquake Engineering, 31(2), 103–121. https://doi.org/10.5459/bnzsee.31.2.103-121

[8] Goretti, A., & Di Pasquale, G. (2002). An overview of post-earthquake damage assessment in Italy. In Eeri invitational workshop. An action plan to develop earthquake damage and loss data protocols, California. https://www.researchgate.net/publication/237399831_AN_OVERVIEW_OF_POST-EARTHQUAKE_DAMAGE_ASSESSMENT_IN_ITALY

[9] Tsuchimoto K, Narazaki Y, Hoskere V, Spencer BF. Rapid postearthquake safety evaluation of buildings using sparse acceleration measurements. Structural Health Monitoring. 2021;20(4):1822-1840. doi:10.1177/1475921720936296

[10] Jalayer, F., De Risi, R. & Manfredi, G. Bayesian Cloud Analysis: efficient structural fragility assessment using linear regression. Bull Earthquake Eng 13, 1183–1203 (2015). https://doi.org/10.1007/s10518-014-9692-z

[11] Gelman, A., Carlin, J.B., Stern, H.S., & Rubin, D.B. (2003). Bayesian Data Analysis (2nd ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9780429258480

[12] European Committee for Standardization. Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings. EN 1998-1:2004, CEN, Brussels, December 2004.
[13] Applied Technology Council. Seismic performance assessment of buildings, Volume 1 – Methodology, Second Edition. FEMA Report P-58-1, Federal Emergency Management Agency, December 2018. https://femap58.atcouncil.org/documents/fema-p-58/24-fema-p-58-volume-1-methodology-second-edition/file
[14] Rodrigo Retamales, Ryan Davies, Gilberto Mosqueda, and André Filiatrault. Experimental seismic fragility of cold-formed steel framed gypsum partition walls. Journal of Structural Engineering, 139(8):1285–1293, 2013. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000657
[15] Petrone, C., Magliulo, G., Lopez, P., and Manfredi, G. (2015) Seismic fragility of plasterboard partitions via in-plane quasi-static tests. Earthquake Engng Struct. Dyn., 44: 2589–2606. https://doi.org/10.1002/eqe.2600
[16] Magliulo, G., Petrone, C., Capozzi, V. et al. Seismic performance evaluation of plasterboard partitions via shake table tests. Bull Earthquake Eng 12, 1657–1677 (2014). https://doi.org/10.1007/s10518-013-9567-8
[17] Petrone, C., Magliulo, G., and Manfredi, G. (2017) Shake table tests on standard and innovative temporary partition walls. Earthquake Engng Struct. Dyn., 46: 1599–1624. https://doi.org/10.1002/eqe.2872
[18] Siavash Soroushian, Esmaeel Rahmanishamsi, Ki Pung Ryu, Emmanuel M. Maragakis, and Andrei M. Reinhorn. Fragility Analysis of Suspended Ceiling Systems in a Full-Scale Experiment. Journal of Structural Engineering, 145(4), 2019. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002273
[19] Tian, Y., Filiatrault, A. and Mosqueda, G. (2014), Experimental Seismic Fragility of Pressurized Fire Suppression Sprinkler Piping Joints. Earthquake Spectra, 30: 1733-1748. https://doi.org/10.1193/111011EQS278M
[20] O'Brien, W.C., Jr., Memari, A.M., Kremer, P.A. and Behr, R.A. (2012), Fragility Curves for Architectural Glass in Stick-Built Glazing Systems. Earthquake Spectra, 28: 639-665. https://doi.org/10.1193/1.4000011
[21] Ozsarac, V., Pereira, N., Mohamed, H., Romão, X. and O'Reilly, G.J. (2025), The Built Environment Data Framework for Simulated Design and Vulnerability Modelling in Earthquake Engineering. Earthquake Engng Struct Dyn., 54: 2651-2670. https://doi.org/10.1002/eqe.4378
[22] Ministero delle Infrastrutture e dei Trasporti. Aggiornamento delle Norme Tecniche per le Costruzioni. Decreto Ministeriale 17 gennaio 2018, Supplemento Ordinario n. 8 alla Gazzetta Ufficiale n. 42, 20 febbraio 2018. https://www.gazzettaufficiale.it/eli/gu/2018/02/20/42/so/8/sg/pdf
[23] Kanda, K., Nakashima, M., Suzuki, Y. and Ogasawara, S. (2021), “q-NAVI”: A case of market-based implementation of structural health monitoring in Japan. Earthquake Spectra, 37: 160-179. https://doi.org/10.1177/8755293020935884