

Issues in the fragility analysis of non-structural elements and the role of structural health monitoring

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Abstract. Non-structural elements (NSEs) are critical to a building's seismic performance and often account for the largest share of repair and recovery costs when structural integrity remains intact. This paper examines data from commercial buildings equipped with structural health monitoring (SHM) systems, alongside insights from building manager interviews following the 2018 Osaka earthquake in Japan. The findings indicate that existing fragility models may underestimate NSE damage, as they fail to fully represent in-situ conditions. Several factors contributing to this discrepancy are identified, including installation variability, interactions with other building components, workmanship quality, and the effects of wear and ageing. SHM data are shown to provide a robust basis for refining fragility models, offering a more realistic alternative to laboratory-based experimental data. In addition, experiences and lessons drawn from past events highlight the potential of SHM-informed fragility analysis to advance future research and support the development of smarter, more resilient strategies for managing earthquake-induced damage.

Keywords: non-structural elements, fragility function, structural health monitoring, 2018 Osaka earthquake.

1. INTRODUCTION

Non-structural elements (NSEs), such as partitions, windows, furniture, and equipment, typically do not significantly contribute to a building's load-bearing system, but can suffer significant damage during earthquakes. While seismic codes have historically prioritised life safety, attention to NSEs has grown as their failures often impair building functionality, cause economic loss, and affect recovery. Early recognition of this issue dates back to Engle [1929], who stressed that neglecting NSEs was impractical given their high cost and impact on a building's functionality. Since then, guidelines and experimental studies [FEMA 2012; Filiatrault et al. 2001; NIST 2017; Taghavi and Miranda 2003] have highlighted their vulnerabilities. Japan's seismic design history illustrates this evolution. Initially focused on structural safety, limited consideration of NSEs led to repeated damage in major earthquakes, such as the 1978 Miyagiken-oki and 1995 Kobe events. Although structural performance improved, NSE damage, especially to equipment and machinery, exposed risks to business continuity, prompting the development of installation guidelines. However, standardisation remains difficult due to the proprietary and diverse nature of NSEs. The introduction of performance-based earthquake engineering (PBEE) and frameworks such as FEMA P-58 [2012] has enabled probabilistic assessment of building performance, extending beyond life safety to include repair costs, downtime, and functional losses. These concepts have also been extended to the seismic risk assessment and classification of NSEs also [Merino et al. 2023; O'Reilly and Calvi 2021]. These advances underline the critical role of NSEs in determining seismic resilience and post-earthquake recovery. This paper discusses some observed issues in the development of fragility functions for NSEs. It uses past observations and presented by O'Reilly et al. [2024] as its starting point to highlight some issues that are typically overlooked, especially when referring to experimental testing of NSEs in laboratory conditions. Additional discussion points surrounding the potential for structural health monitoring (SHM) solutions based on recent experiences in Japan by Fukutomi et al. [2025] are also presented.

2. ISSUES IN FRAGILITY FUNCTION DEVELOPMENT FOR NSES

To evaluate the risks linked to NSEs, researchers commonly use fragility functions. These functions express the probability of different damage states (DSs), such as window cracking, as a function of an engineering demand parameter (EDP), like storey drift. They are usually developed from experimental data, which remains the most widely used source despite being limited in availability, as highlighted by Bianchi and Pampanin [2022]. Still, laboratory testing does not always capture real-world conditions, and several such limitations are discussed here.

2.1 INSTALLATION CONDITIONS

The first issue concerns the difference between how NSEs are tested in laboratories and how they perform in real buildings. Bianchi and Pampanin [2022], in their review of previous studies, highlighted that fragility functions derived from experiments are strongly affected by connection details. This was evident for NSEs that are vulnerable to both storey drift and floor accelerations. For instance, Huang et al. [2022] showed through shake table tests on partition walls that boundary conditions can alter seismic fragility by as much as 42%. Similarly, Filiatrault et al. [2001] emphasised that while code-based force calculations for NSEs may be imperfect, their actual damage resistance often depends more on proper construction and detailing than on the intensity of shaking. Tasligedik et al. [2012] also observed that the poor seismic performance of drywall partitions during the 2010 and 2011 Canterbury earthquakes in New Zealand was largely due to inadequate protective technologies and construction details.[FEMA 2007]

Bianchi and Pampanin [2022] argued for improving detailing practices to achieve "low damage detailing" and enhance the overall resilience of NSEs, which raises an important consideration. Since most fragility

functions used in damage and loss assessments come from limited laboratory testing, and given that NSE behaviour is highly sensitive to connection details, one must ask: how accurately do these laboratory connection details represent reality? Laboratory experiments are often constrained by available setups, which may require compromises for both structural and non-structural components. While this may be less critical for structural elements, where key regions are typically away from test connections, it becomes a major concern for NSEs whose performance depends heavily on interface connections. As a result, the representativeness of some experimental fragility data, and the functions derived from them, may be questionable when compared to real-world conditions.

2.2 LOADING PROTOCOLS

The second issue concerns the loading protocols used in experimental testing and the way loads are applied to specimens. While loading protocols for structural elements have been widely studied and documented [Mergos and Beyer 2014; Richards and Uang 2006], guidance for NSEs has often relied on FEMA 461 [2007]. However, it is increasingly recognized that the number and amplitude of load cycles (Figure 1(c)) have a major influence on energy dissipation and damage accumulation. For instance, Gentile and Galasso [2021] highlighted the role of hysteretic energy in fragility assessments, Wilding et al. [Wilding et al. 2017] examined how loading protocols affect unreinforced masonry walls, whereas Gentile et al. [2025] has provided further insights into this topic through experimental testing with different energy inputs for a given level of drift demand to examine the damage induced in masonry infill panels. Although these studies focused on structural elements, the same principles apply to NSEs: loading protocols must realistically represent seismic demands.

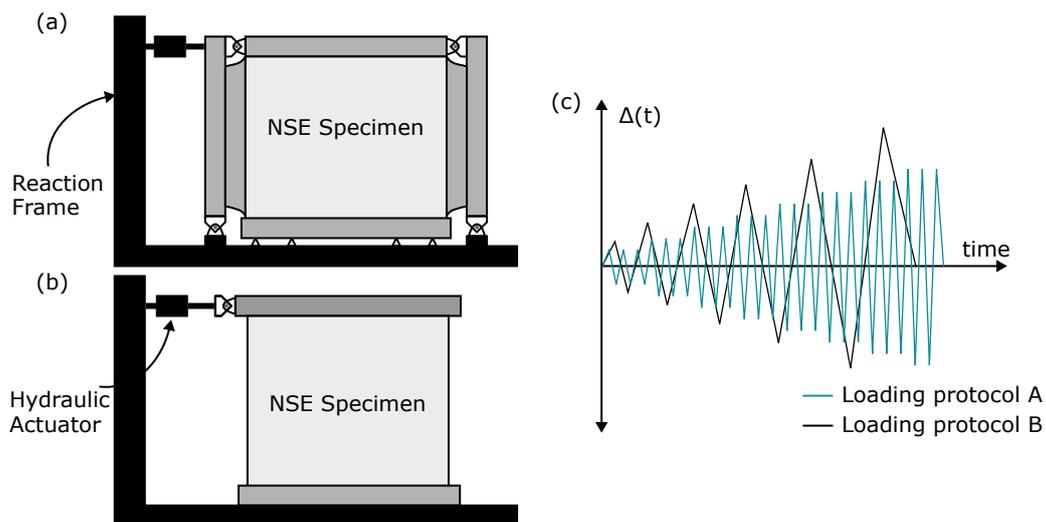


Figure 1. Illustration of (a)-(b) different experimental setup configurations to conduct a quasi-static test on an NSE specimen, and (c) the different loading protocols that may be applied

Beyond the choice of protocol itself, there is also the question of how loads are physically applied during testing. For example, Bianchi and Pampanin [2022] noted that early investigations into curtain wall performance in the 1960s [1961] considered only in-plane behaviour, whereas out-of-plane effects are now understood to be equally important. Moreover, cladding systems interact with the structural frame, meaning isolated tests may not capture their true response. Similarly, Lee et al. [2007] pointed out that many earlier studies on drywall partitions did not mount specimens within realistic frame systems. Figure 1(a) shows the setup they used for drywall partition testing, while Figure 1(b) depicts the quasi-static setup used by Retamales et al. [2013] for gypsum partitions with cold-formed steel frames. Although both setups targeted similar NSE types, they subjected specimens to different deformation and force conditions. Each approach may be valid in certain contexts, but combining their results risks inconsistency.

Ultimately, many experimental campaigns have been carried out using the best methods available at the time. Yet, as research evolves, it is becoming clear that older data may suffer from limitations. Nevertheless, these data remain embedded in available datasets and continue to inform many of the fragility functions currently in use for NSEs.

2.3 INTERACTION WITH OTHER NSEs

Another limitation of fragility functions derived from single-specimen experimental tests is their inability to capture adverse interactions between different structural and non-structural elements within a building. This issue has been repeatedly observed in past earthquakes. For example, Baird and Ferner [2017] reported several cases during the 2016 Kaikōura earthquake in New Zealand where ceiling failures were triggered by interactions with services, partitions, and the main structure. Similarly, Chavez and Binder [1996] described extensive non-structural and contents damage at the Veteran Administration hospital in Sepulveda after the 1994 Northridge earthquake. In that case, most of the losses were due to leaking water pipes, which damaged underlying components and caused service interruptions—failures driven not by the pipes' own seismic fragility, but by the secondary effects of interaction. Comparable findings were noted by Miranda et al. [2012] for the Hospital de San Carlos and residential buildings in Santiago following the 2010 Chile earthquake, and by Yoshizawa et al. [2014], who reported that much of the NSE damage during the 2011 Tohoku earthquake in Japan resulted from interactions between equipment and surrounding elements, rather than from direct equipment failure.

These interactions have a major influence on both the extent of damage and the associated loss estimates. Relying solely on fragility functions that neglect such effects is unconservative and can lead to underestimation of economic losses and reduced accuracy in predicting post-earthquake functionality, as seen in the Northridge hospital case. Some of these limitations can be addressed through approaches such as the storey loss functions proposed by O'Reilly and Shahnazaryan [2024], which account for inter-element damage-state dependencies. For instance, as Chavez and Binder [1996] highlighted, the loss of hospital furnishings may be triggered not by their direct fragility, but by damage to nearby water piping systems.

2.4 QUALITY OF WORKMANSHIP DURING INSTALLATION

Another concern is the difference in workmanship between laboratory-installed test specimens and those installed in real buildings. The representativeness of laboratory specimens is questionable, as contractors tasked with building a small number of NSE specimens for detailed scrutiny are likely to devote more care and precision than they would when installing dozens of similar elements in practice. This does not imply that real-world installations are of poor quality; rather, while construction standards are typically met, test specimens often reflect a much higher standard of workmanship. The PACT fragility function library partially acknowledges this issue by allowing users to specify installation quality for each NSE fragility function set, though no broad guidance is provided on how to apply such distinctions.

2.5 WEAR, TEAR AND UNANTICIPATED INTERVENTIONS

Another factor to consider is that NSEs are elements with which occupants regularly interact and use over time. A door or window that has been opened and closed for years is unlikely to behave the same as a pristine specimen tested in a laboratory. Continuous use can gradually wear down connections and moving parts, allowing for slightly more flexibility and potentially greater resilience to seismic demands. Similarly, piping systems that have been in service or subjected to maintenance may respond differently than new installations. Unplanned modifications can also alter performance—for instance, changes in pipe bracing, openings cut into partitions to accommodate other systems, or window glass replaced with more efficient types. In addition, cumulative effects from past minor earthquakes may cause subtle, unrepaired damage that alters behaviour without being classified as “damage”. While these details may appear minor, previous studies have shown that such factors can meaningfully influence NSE performance, making them important to acknowledge in seismic damage assessments.

3. STRUCTURAL HEALTH MONITORING

The points discussed above highlight several ways in which laboratory-based experimental data for NSEs may fall short of accurately representing real conditions, largely due to inherent testing constraints. This does not diminish the value of experimental studies, but it does underscore that their limitations are widely recognised and contribute to overall uncertainty. An alternative approach to developing fragility functions, one that could address many of these challenges, is the collection of data directly from in-situ NSEs through structural health monitoring (SHM). In Japan, such a system has been under development for many years, which is termed q-NAVI has been discussed by Kanda et al. [2021].

3.1 IMPROVED FRAGILITY FUNCTIONS

A major challenge in developing fragility functions from SHM data combined with post-earthquake inspection reports lies in the format of the information obtained. In controlled experimental testing of NSEs (e.g., when applying a quasi-static protocol) multiple specimens can be tested, and the precise engineering demand parameter (EDP) at which each damage state (DS) occurs is recorded. With this data, fragility functions can be derived using the method of moments, known as Method A [Porter et al. 2007]. In contrast, SHM and post-earthquake inspections typically provide only the maximum observed EDPs alongside the final DSs of NSEs. This is a crucial difference, as the recorded EDP reflects the maximum experienced demand, not the actual value at which the DS was triggered. To handle such data, Porter et al. [2007] proposed an alternative “Method B”, which relies on bounding information.

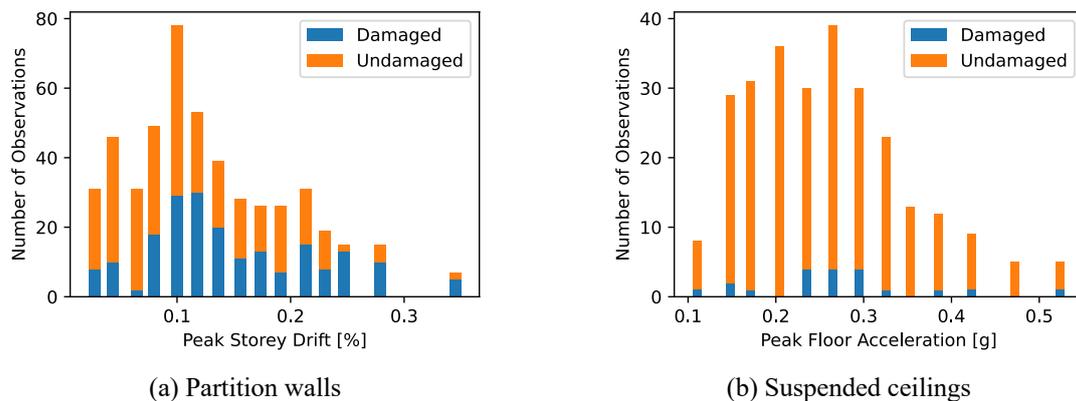


Figure 2: Binned distribution of damage observed following the 2018 Osaka earthquake

For illustration, Ogasawara et al. [2020] collected data from 26 office buildings (7–20 storeys, built between 1974 and 2009) surveyed after the 2018 Osaka earthquake, which was later used by O’Reilly et al. [2024] to develop fragility functions. None of the buildings experienced significant structural damage, but the q-NAVI system provided maximum demand data, while additional surveys assessed usability. Damage classification relied mainly on interviews with building managers about two months after the earthquake, supplemented by photographs taken immediately after the event to confirm early repairs. The dataset included eight NSE typologies, though detailed information was only available for partition walls and suspended ceilings, which showed the most severe damage. Importantly, survey data was recorded in binary form (damaged vs. not damaged). Future studies could improve on this approach by recording graded levels of damage (e.g., light, moderate, extensive), thereby providing a more refined basis for fragility function development.

For partition walls, damage data was collected in both orthogonal directions of the surveyed buildings, yielding a total of 494 observations. These results were grouped into bins and are shown in Figure 2(a). For suspended ceilings, 270 observations were recorded, with the corresponding binned data presented in Figure

2(b). The results clearly indicate that partition walls experienced significantly more cases of damage compared to ceilings.

Fragility functions were developed using both Method B from Porter et al. [2007] and the maximum likelihood estimation approach outlined by Baker [2015]. The results, shown in Figure 3, demonstrate that the Porter et al. [2007] method provided a poor fit to the data. Although the curve follows the available observations closely, it fails to account for data truncation, meaning that additional data would likely shift the trend toward more realistic behaviour. This shortcoming is reflected in the unrealistically high probability estimates at low demand levels. In contrast, the maximum likelihood approach of Baker [2015] produced a much better fit. Baker [2015] also critiqued Method B, noting that applying it in this context disregards the non-uniform variance of the dataset, thereby violating the assumptions of least-squares regression. As seen in Figure 3, this results in inflated probability estimates at very low demands, which is counterintuitive. The issue is particularly evident in the ceiling fragility function [Figure 3(b)], where the probability of damage is nearly constant across all demand levels. By comparison, maximum likelihood fitting captures the overall data trend far more reliably.

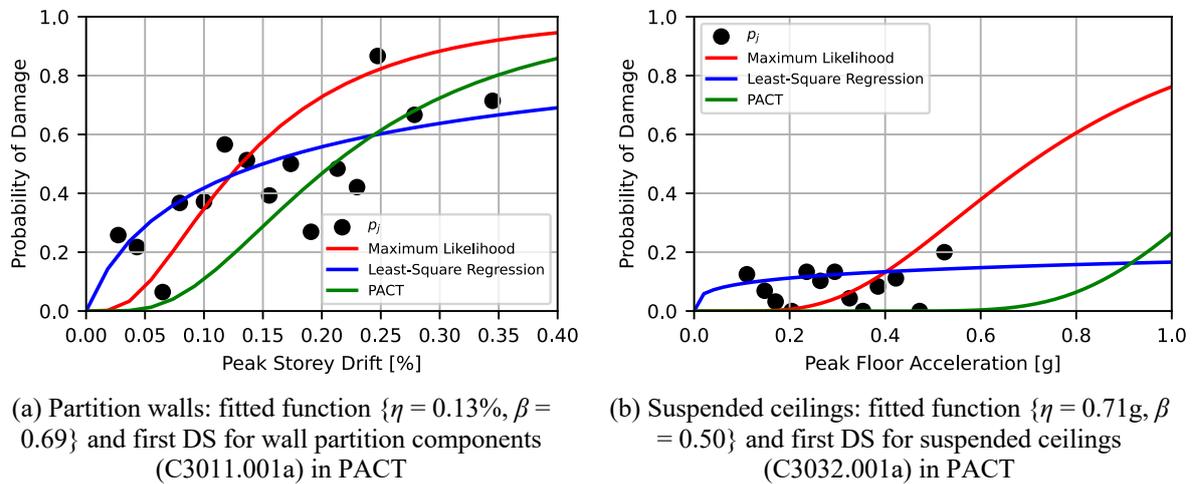


Figure 3: Illustration of fragility functions fit using the maximum likelihood method using data collected from the q-NAVI system during the 2018 Osaka earthquake compared with a corresponding fragility function from PACT

While the discussion has so far been limited to the fitting of the fragility functions to the SHM data, another important observation can be made. This is in relation to the previous discussion in Section 2, whereby many existing fragility functions developed based on experimental testing may not be entirely representative of the in-situ reality. To gauge this, comparable fragility functions for both partition walls and suspended ceilings were extracted from the PACT library and plotted in Figure 3. What is immediately clear is that both fragility functions from PACT have median values much higher (around 38% in both cases) than those derived using maximum likelihood fitting on actual data observed during earthquakes. The dispersion values tended to be quite similar, which is contrary to the general recommendations of FEMA P-58 to account for these issues in fragility function development.

Although these findings are preliminary, the relatively large dataset provides support for many of the earlier arguments when compared with actual field evidence. The conclusions draw not only on further analysis and interpretation of the SHM data, but also on the many small observations noted by researchers across numerous NSE experimental campaigns over the years. The key takeaway is that SHM systems such as q-NAVI can serve as a valuable complement to experimental testing, offering an improved basis for developing fragility functions for NSE damage.

3.2 REFLECTIONS BASED ON JAPANESE EXPERIENCE

Since the 2011 Tohoku earthquake, SHM for buildings has gained growing attention in Japan, especially in relation to business continuity and functional recovery. Most systems are market-driven, with building owners choosing to install SHM at their own expense to enable rapid post-earthquake condition assessments, typically classified with *Green*, *Yellow*, or *Red* tags. Fukutomi et al. [2025] report on experiences with SHM to date, including data use, monitoring practices, and engagement with building owners, highlighting three key insights, particularly concerning the *Caution (Yellow)* tag.

The first opinion is that the damage criteria, namely the thresholds separating the three tags, should not be regarded as fixed but should instead be updated in light of experience and newly collected data. Immediately following noticeable shaking, one of the three statuses: *Green (Safe)* (i.e., minimal or no damage, continued occupancy ensured), *Caution (Yellow)* (i.e., some damage, no immediate evacuation required, detailed inspection recommended), or *Danger (Red)* (i.e., severe damage, evacuation advised) is provided by the SHM system to building managers and occupants. The *Green (Safe)* classification is based on conditions in which the stresses in primary structural members remain below their short-term allowable limits. A signal warning of potential non-structural damage is triggered when maximum floor acceleration reaches 0.1g. Default threshold values for maximum story drift ratios are set at 1/350 and 1/250 to define the boundaries among *Green*, *Yellow*, or *Red*. These thresholds are considerably smaller than the limits of 1/200 and 1/120 established in modern design codes, the difference reflecting the conservatism adopted to account for uncertainties. After past earthquakes, site visits were conducted, and building damage was observed. It was confirmed that the maximum story drift estimated by the SHM system was consistent with actual behaviour, though structural damage remained minor. This outcome reflected the conservatism of the threshold values. With the agreement of the building owners, the threshold values were subsequently relaxed for those buildings. The experience provided clear evidence that actual earthquake response data can be used to refine and adjust threshold values, thereby making the categorisation of damage states more appropriate.

The second opinion is that SHM represents one of the most effective approaches for characterising the damage and fragility of major non-structural elements, with the *Caution (Yellow)* tag being particularly relevant to non-structural damage in its early stages. Past earthquakes have provided numerous examples in which damage to manufacturing plants and the disruption of machinery severely impeded business continuity. Since the 2000s, when several large earthquakes affected Japan, increasing attention has also been directed toward non-structural damage in office buildings. Reports from these events indicated that the onset and progression of non-structural damage frequently preceded structural damage, with many cases observed where only non-structural elements were affected. Significant efforts have since been devoted to quantifying non-structural damage. However, this task has been constrained by certain characteristics unique to non-structural elements. In particular, their performance is strongly influenced by the manner in which they are connected to primary structural members. The quality of detailing, whether adequate or inadequate, can result in markedly different force transfer to these elements. Fragility functions are typically used to represent non-structural damage, requiring data that defines the relationship between external demands and the resulting level of damage. As previously noted, obtaining such data is far more challenging for non-structural elements than for primary structural members, making its accumulation difficult. In this context, SHM offers considerable value. As illustrated in the preceding subsection, SHM is capable of providing critical data on non-structural elements, thereby addressing a long-standing gap in fragility function development.

The third opinion is that the *Caution (Yellow)* status is a beneficial message for building owners and managers who have established contingency plans supported by readily available maintenance personnel and engineers. In contrast, when such plans are absent, the *Caution (Yellow)* message often generates concern or fear, which in turn discourages the adoption of SHM. From interactions with owners and managers of SHM-equipped buildings, it has been reconfirmed that large corporations managing multiple properties generally possess robust support systems for responding quickly to earthquakes and other hazards. In such

cases, maintenance staff are permanently stationed in each building, continuously monitoring the operation of structural, mechanical, and utility systems such as electricity, gas, and water. In addition, permanent contractual relationships are maintained with construction companies that can be dispatched immediately to address post-event problems, with priority given to the affected building. For owners without comparable support systems, however, the *Caution (Yellow)* status functions less as a useful warning and more as a source of frustration, since no effective action can be taken in response and effectively underscores the lack of adequate planning.

4. SUMMARY AND CONCLUSIONS

This paper has examined key challenges in estimating earthquake-induced damage to non-structural elements (NSEs) and the broader implications for building performance. Drawing on observations from commercial buildings affected by recent Japanese earthquakes, the discussion compared field evidence with developments in current research, particularly in relation to fragility functions and the emerging role of structural health monitoring (SHM). While SHM is often deployed to assess structural safety after major events, it also provides valuable data that can inform the development of more representative fragility functions for NSEs. From the discussions and examples presented, the following conclusions are drawn:

- Fragility functions are essential for estimating damage to both structural and non-structural components. However, those derived for NSEs often lack representativeness, due to factors such as installation conditions and loading protocols in laboratory testing, interactions with other elements, variability in workmanship, and wear or degradation over time. These issues were shown to significantly influence NSE performance and the reliability of associated fragility models.
- SHM offers a promising approach for deriving more representative fragility functions, particularly in cases where structural safety is not immediately at risk. Data collected from several Japanese buildings enabled the development of fragility functions for partition walls and suspended ceilings. Comparison with existing literature demonstrated that these elements may be more vulnerable than suggested by experimental fragility functions, underscoring the importance of real building demand data.
- SHM data combined with interviews with building owners and managers highlighted three key insights. First, the thresholds that define the *Green*, *Yellow*, and *Red* damage tags should not be considered fixed, but rather updated as new data and experience become available. Second, SHM provides one of the most effective means of characterising damage and fragility for major NSEs, with the *Yellow (Caution)* status being particularly relevant for identifying initial stages of non-structural damage. Third, while the *Yellow* status is beneficial for organisations with strong contingency plans and dedicated support systems, it can cause concern for those lacking such resources, discouraging SHM adoption in some cases.

Overall, the study underscores the limitations of experimental fragility models for NSEs and highlights SHM as a complementary and powerful tool for advancing more realistic fragility assessments.

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