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RESEARCH ARTICLE

On the fragility of non-structural elements in loss and recovery: Field observations from Japan

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Abstract

The role of non-structural elements (NSEs) in the seismic performance of buildings has been highlighted in past years. Research studies following state-of-the-art methodologies generally find that when the structural collapse is not of significant concern, NSEs tend to dominate the repair costs and financial investment required in a building. This paper examines field observations from interviews and data collected from commercial buildings via structural health monitoring (SHM) following the 2018 Osaka earthquake in Japan. It suggests that fragility functions used in current methodologies for estimating NSE damage may not be entirely representative of the in-situ reality and possibly underestimate actual damage. Additionally, interviews with building owners/managers indicate that the alarm and financial impact of NSEs was not as critical as anticipated, with much of the observed NSE damage not of serious concern and tolerable in many cases. This article provides discussion and insight into possible causes for these differences before discussing how current methodologies can benefit from these observations. It is believed that many of the fragility functions currently used to estimate NSE damage may not be representative because of differences in installation conditions and loading protocols used in experimental testing, possible interaction with other elements, variability in the quality of workmanship during installation and possible wear, tear and degradation during service. On the other hand, it is seen how SHM data recorded during seismic events may provide valuable data for an alternative means to develop fragility functions. Furthermore, it is seen that when building recovery states (RSs) other than the implicitly assumed 'full recovery' state used in guidelines like FEMA P-58 are explored, the role of NSEs in direct monetary losses significantly reduces. This coincides with the field observations in Japan regarding the impact of NSEs and supports the recent developments in functional recovery on what building owners and occupants are prepared to tolerate post-earthquake. It indicates that when discussing the relative importance of different building performance groups, it is vital that the expected RS is also stated, as for most decision-makers following major events, functionality rather than full recovery remains the primary goal; hence, repairs and proactive measures should bear this in mind for more effective use of resources.

KEYWORDS
2018 Osaka earthquake, fragility function, functional recovery, losses, non-structural elements

1 INTRODUCTION

Non-structural elements (NSEs) are components of a building that do not form part of the structural load-resisting system, such as interior walls, doors, windows, cabinets, furniture, and other items that are not essential to the stability of the structure. Earthquake engineering has traditionally focused on life-safety objectives during building code development, meaning that the primary goal of engineers is to save lives and reduce the potential for injuries during seismic events. It is also important to recognise that seismic codes have been put into effect and maintained at different times around the world, each with its own specific requirements.

Early observations on the relevance of NSEs date back to comments made by Engle,[1] who noted that a building which sustains significant damage to its NSEs, such as partitions and finishes, becomes useless after an earthquake, even if it manages to avoid structural collapse. They deemed it irrational to concentrate only on the building frame as its cost seldom exceeds 15% of the total. Over the years, there have been several advancements in creating guidelines and conducting experimental test campaigns[2,3] to highlight and investigate the potential vulnerabilities of NSEs. These have culminated in more formal recommendations by FEMA[4] and NIST,[5] for example.

In the case of Japan, the history of seismic design and construction is marked by significant shifts and challenges. In the aftermath of World War II, there was limited emphasis on modern seismic design until the 1960s. During that period, the focus was primarily on life safety in structural design, with little attention to NSEs. In the 1970s, modern seismic design gained traction, resulting in buildings with higher seismic capacity. However, this led to increased damage to NSEs, exemplified by the 1978 Miyagiken-oki earthquake, which exposed vulnerabilities in NSEs.[6] In the 1980s, guidelines were introduced to address NSE safety (i.e., NSEs,[7] and major types of equipment[8]), but public awareness remained relatively low due primarily to a lack of significant earthquakes for some years after the 1978 Miyagiken-oki earthquake. The turning point came in 1995 with the devastating Kobe earthquake. It caused numerous damage cases to NSEs, but they were entirely overshadowed by the most severe structural damage that involved a death toll of over 6000. By the early-2000s, Japanese seismic design had stabilised, incorporating lessons from the Kobe earthquake. In the 2000s, significant earthquakes (between 6.7 and 7.3 in magnitude and reaching the level of ground shaking that corresponds to the Level 2 (equivalent to DBE) design earthquake) shook various parts of Japan (e.g., refs. 9–14). Damaged patterns reported following the earthquakes revealed that the initiation and progress of NSE damage commonly preceded those of structural damage, with many instances where damage occurred only in NSE. Notably, the 2004 Chuetsu and 2007 Chuetsu-oki earthquakes revealed a new challenge: while structural performance was generally good, some manufacturing plants suffered from severe damage to machinery, affecting production. It led to the emergence of concepts like 'business continuity planning' and 'supply chains', emphasising the need to assess and control damage to NSEs. Despite such NSE damage and renewed attention, comprehensive efforts to improve and generalise the NSE design remained limited. The primary obstacle was the diversity in design and construction even within the same category of NSEs. Unlike structural elements, which have standardised design procedures, NSEs are proprietary most commonly, with varying materials, details, connections, and fabrication methods. To cope with this complexity, professional organisations representing respective NSEs have prepared and updated installation guidelines by which the relevant supplies and constructors must abide so that the NSEs can be accommodated into the main structures without premature failures.

With the advent of the Pacific Earthquake Engineering Research (PEER) Centre's performance-based earthquake engineering (PBEE) framework,[15] seismic engineers can now estimate the damage to different kinds of building components in a more probabilistic manner. The framework outlined in FEMA P-58[16] then allows users to extend this expected damage to provide estimates of the expected repair costs, downtime and loss of life in a building following an earthquake. This has been widely adopted in recent years, and many studies have repeatedly highlighted the important role of NSEs in accumulating monetary losses. Over the past two decades, engineers have found that using decision variables such as monetary loss is a much more effective way of communicating seismic risk to clients and stakeholders. Implementing a

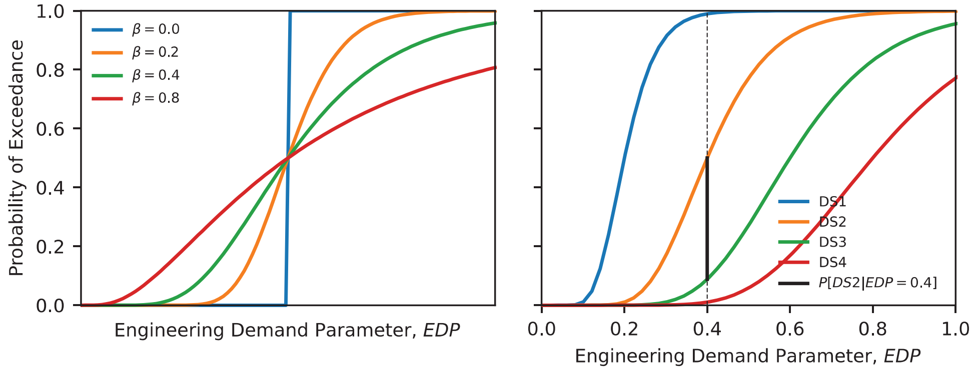


FIGURE 1 Illustration of fragility functions (left) depicting various levels of uncertainty for a fixed median, and (right) how they are used to estimate the DSs in an NSE for a given level of demand.

methodology and framework like that outlined in FEMA P-58 comes with many critical assumptions regarding seismic hazard, structural modelling, etc.

The objective of this paper is to explore the following two assumptions in detail among many others. One crucial assumption is related to estimating NSE-induced repair costs and it is noted that their damage can be accurately estimated using fragility functions generally available in large databases such as that provided in the Performance Assessment Calculation Tool (PACT) library.[16] Another crucial assumption is regarding the level of recovery expected by building owners following these post-earthquake repair actions. That is, is the building expected to be fully restored to its pre-earthquake condition, possibly with some improvements, or would a reduced level of repair be deemed acceptable? These two aspects were chosen because interesting observations relevant to them were acquired from some recent earthquakes in Japan, where structural health monitoring (SHM) data and damage reports and interviews with commercial building managers and owners have been made available.

The paper consists of four parts. First, it examines how fragility functions tend to be derived via experimental testing and other means, pointing out some critical aspects that are perhaps not reflective of the reality encountered in practice. Second, the SHM data collected from several commercial buildings following the 2018 Osaka earthquake in Japan is elaborated to derive fragility functions for typical NSEs found in such typologies. This data are seen to support the issues noted and an improved means to estimate NSE fragility functions in the future is described, where more integrated monitoring systems could be key for widespread success. Third, the expected level of recovery that building owners and managers anticipate is discussed in relation to the reported consequences following the same earthquake. It is seen how many of the recent developments in the field of functional recovery are very relevant. NSEs have long been touted as a major issue to address when collapse and life safety are not critical in buildings, although field evidence collected in Japan tends to indicate that this may be somewhat of an exaggeration in some cases, specifically in the case of commercial building with one centralised owner and decision-maker. Fourth, a case study is presented to examine how the expected recovery level will impact the repair cost distribution. It will be seen that depending on the level of recovery sought, the relative importance of NSEs is notably impacted. Overall, the paper provides insight into the actual impacts of NSE damage in commercial building following major earthquakes. It is envisaged that by offering an alternative perspective, some misleading conclusions about the relative importance of NSEs can be avoided and the overall approach to preserving building functionality can be strengthened.

2 | USE OF FRAGILITY FUNCTIONS IN NSE DAMAGE ASSESSMENT

2.1 | The need for fragility functions

To quantify any of the three main risks associated with NSEs,[4] their performance at a given level of demand is typically quantified using a fragility function (Figure 1). A fragility function is a probabilistic relationship between a component's predefined set of consequences, or damage states (DSs), (e.g., window pane cracking) and the engineering demand parameter (EDP) it is assumed to be sensitive to (e.g., storey drift). The key feature of fragility functions is that they recognise damage uncertainty by providing a probability of a DS for a given level of demand. This is opposed to the categorical yes/no evaluation of whether a damaged state has been reached (i.e., via the deterministic step function shown in Figure 1 (left) for $\beta = 0.0$) that most codes or guidelines utilise. A lognormal distribution characterised by a median, η, and dispersion, β, is the most common means to describe fragility functions and is given by:

$$P\ (DS|EDP\ =\ edp) = \Phi\left(\frac{\ln\left(\frac{edp}{\eta}\right)}{\beta}\right) \tag{1}$$

The use of fragility functions reflects reality and integrates well with the probabilistic nature of the PEER PBEE framework, which utilises the expected distribution of EDP for a given seismic intensity to evaluate the probabilities of each NSE's expected damage via their fragility function (Figure 1 (right)). Knowing the probability of each DS for a given NSE, the repair cost can be used to estimate the expected monetary loss associated with that NSE. When applied to an entire building's damageable inventory, this can estimate the expected monetary loss for that level of shaking in the building. Using a decision variable like monetary loss has provided engineers with much more apt ways of communicating seismic risk to clients and stakeholders over the past two decades. When considering the recent reflections for Japan by Suzuki et al.,[17] it is clear there is still work to be done on some fronts worldwide regarding the adoption of risk-based approaches in seismic design practice. The PEER PBEE framework has been formalised via the provision of the FEMA P-58 guideline[16] initially published in 2012 by the Federal Emergency Management Agency in the US, where quantities like expected loss are now commonplace among seismic engineers.

2.2 | Methods to derive fragility functions

To derive the fragility functions needed to assess NSE damage, data and expertise are required. This ensures that the median and dispersion pair $\{\eta, \beta\}$ for each DS represents the expected NSE seismic behaviour. Stemming from the long tradition of experimentally testing structural elements via quasi-static or dynamic lateral loading, a similar approach has been adopted for NSEs. Porter et al.[18] outline six quantitative procedures for developing fragility functions for use in damage and loss assessment through Method (A) actual demand data; Method (B) bounding demand data; Method (C) capable demand data; Method (D) derivation; Method (E) expert opinion; and Method (U) updating using new observations. Methods A–C are based on experimental data, where the key differences are in whether the DS of interest was actually observed in the experiment and how to derive the fragility function in cases when it is not observed for some or all test specimens. FEMA 461[19] provides details on recommended procedures for developing such experimental data, while other considerations have been made in other countries.[20] Method D involves deriving fragility functions using a suitably calibrated numerical model, such as Echevarria et al.[21] for ceiling systems or Salmasi Javid et al.[22] for gypsum partitions. Method E relies on expert opinion in the absence of data or any feasible numerical modelling approach. Method U describes how to improve an existing fragility function using new observations. These were adopted and are described in Appendix H of FEMA P-58, which has formed the basis for over 700 fragility functions included in the PACT library.

2.3 | Observed issues and potential discrepancies

While the methods described in Section 1.2 have been widely adopted, there are several issues and potential discrepancies that may arise. Two minor points relate to the fitting of the fragility function with a lognormal distribution. Sometimes, the data available for a certain NSE may not actually follow a lognormal distribution, making it inaccurate to fit a median and dispersion pair $\{\eta, \beta\}$. Also, there may be situations where the fragility functions for different DSs of the same NSE intersect one another, producing meaningless negative probabilities of DSs. These two issues and ways to address them have been discussed in Porter et al.[18] and are not discussed further here.

Of more interest to the present discussion is the means with which the data to fit such fragility functions is obtained. In most cases, it is implied that this data are derived from experimental testing. This is evident from the recent literature review provided by Bianchi and Pampanin,[23] who note that experimental testing has become one of the most common means of deriving NSE fragility functions, even if such data are not always plentiful and available. Dhakal et al.[24] provide an overview of the different experimental test campaigns carried out in New Zealand in recent years to characterise the vulnerability of NSEs. However, several situations may arise in which the experimental testing of NSEs in a laboratory setting may not adequately represent reality. These situations are discussed herein.

2.3.1 | Installation conditions: Laboratory versus in-situ reality

The first point relates to the installation conditions of an NSE within a laboratory versus the actual in-situ conditions. Bianchi and Pampanin[23] in their review of past work, note how the fragility functions derived from experimental testing of NSEs are significantly influenced by their connection details. This was the case for NSEs sensitive to both storey drift and floor accelerations. For example, Huang et al.[25] observed from shake table testing on partition walls that the boundary condition can impact seismic fragility by up to 42%. In a review of NSEs, Filiatrault et al.[3] noted that although NSEs may have shortcomings in code-design force computation, their resistance to damage may depend more on proper construction and detailing and not the amount of shaking they experience. Tasligedik et al.[26] also reported that the lack of technologies and construction details to protect drywall partitions from damage in the 2010 and 2011 Canterbury earthquakes in New Zealand significantly affected their poor seismic performance.

While the discussion of Bianchi and Pampanin[23] was centred around the idea of improving the construction details to give 'low damage detailing' and improve general NSE behaviour for the future, it is a point worth reflecting on. If the NSE fragility functions currently used in most damage and loss assessments have been derived from (often scarce) experimental data developed in laboratories, and if these NSEs' behaviour has been observed to be significantly impacted by connection details, the question becomes: how representative are the connection details used in experimental testing versus reality? Laboratories are often constrained by the test setups they have available; hence, some compromises may be needed both for structural and non-structural elements. This may be less of a problem for structural elements whose critical regions are located away from the connection to the test setup. However, when the interface connections play a crucial role, the representativeness of some NSE experimental data (and the subsequent fragility functions) may be questioned with respect to what is generally encountered in reality.

2.3.2 | Loading protocols and method of application to test specimens

The second issue surrounds the loading protocols used to test specimens experimentally and how these loads are physically applied. The issue of loading protocols to use when testing structural elements is a well-discussed topic, and many examples are available for structural elements.[27,28] In the case of NSEs, the FEMA 461 guideline has become a reference document for many. However, it is becoming increasingly recognised that the number and amplitude of loading cycles (Figure 2C)) when testing specimens play a key role in energy dissipation and damage accumulation. For example, Gentile and Galasso[29] noted the role of hysteretic energy in the DS-dependent fragility assessment of structures, whereas Wilding et al.[30] examined the impacts of loading protocol on the behaviour of unreinforced masonry walls. While these studies did not relate to NSEs, the same basic concepts apply. The loading protocols must maintain a certain level of representativeness compared to the actual seismic demand encountered in reality.

In addition to the anticipated demands experienced by the NSEs and loading protocols developed to represent them in a laboratory, there is also the issue of how these protocols are physically applied to test specimens. For example, Bianchi and Pampanin[23] note how pioneering work on the seismic behaviour of curtain walls was conducted in the 1960s[31] but focused on their in-plane behaviour only. It is now recognised that out-of-plane behaviour also plays a key role and further work can be done to consider that. Also, cladding systems are now known to interact with the structural skeleton they are attached to; hence, testing them independently may be unrepresentative. Lee et al.[32] note in their experimental work on drywall partitions in the mid-2000s that many previous studies had not tested these NSEs mounted within actual frame system representative of reality. Figure 2(A) illustrates the test setup used by Lee et al.[32] for their experimental testing on drywall partition walls. Figure 2(B), on the other hand, also shows a quasi-static test setup used by Retamales et al.[33] for the experimental testing of cold-formed steel-framed gypsum partitions. While these NSE typologies are slightly different, the important point to note is that the conditions under which they were loaded are clearly inconsistent, imposing different deformations and forces in the NSE specimens. Both may be correct in different circumstances, but combining these results may not be strictly correct.

The issue raised here is that many experimental campaigns have been conducted, often using state-of-the-art methods at the time. However, as research advances and knowledge improves, it is clear that past data may possess some practical

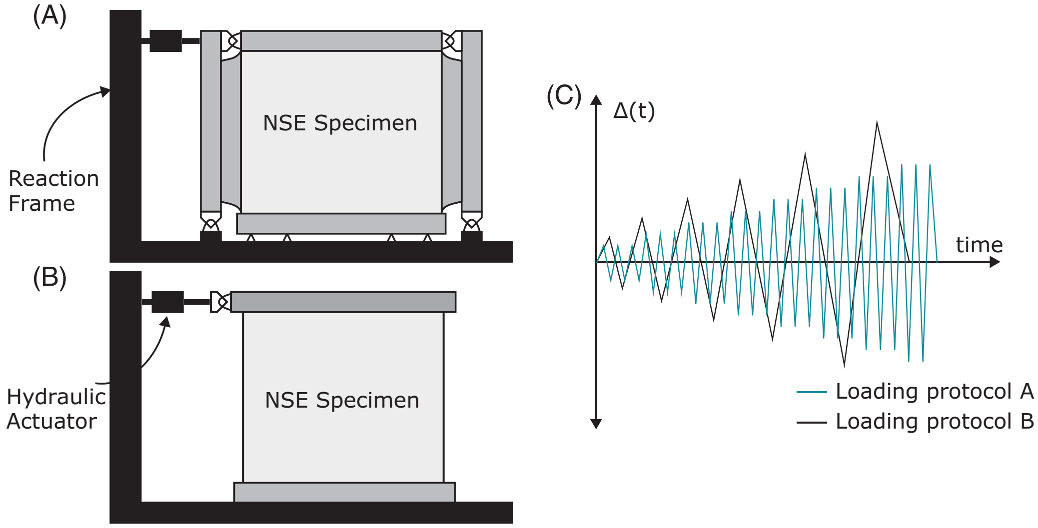


FIGURE 2 Illustration of (A)–(B) different experimental setup configurations to conduct a quasi-static test on an NSE specimen, and (C) the different loading protocols that may be applied.

limitations. The issue is that this existing data permeates the available datasets and likely many NSE fragility functions currently in use.

2.3.3 | Interaction with other elements

The next issue that fragility functions developed from experimental data on single test specimens cannot capture is the potential to adversely interact with other structural and non-structural elements in the building. This is a critical issue that has been reported in the observations following several past earthquakes. For example, Baird and Ferner[34] noted several examples during the 2016 Kaikoura earthquake in New Zealand of damage to ceilings resulting from the interaction with other elements such as services, partitions and the structure itself. Chavez and Binder[35] reported on how there was extensive damage to NSEs and the general contents of the Veteran Administration hospital in Sepulveda following the 1994 Northridge earthquake. Most of the destruction was caused by leaking due to water pipe damage. This meant that there was water damage to the components below, resulting in complete loss and also interruption, but that this was not due to the NSE's own vulnerability to shaking. Similar observations were reported by Miranda et al.[36] for the Hospital de San Carlos and also the residential buildings in Santiago following the 2010 Chile earthquake. Yoshizawa et al.[37] also noted that the vast majority of NSE damage following the 2011 Tohoku earthquake in Japan was reportedly because of interaction between equipment and NSEs, rather than damage to the equipment itself. These kinds of interactions significantly impact the resulting damage and estimated losses in a building. Utilising fragility functions that cannot capture these effects is unconservative and can impact the economic loss and overall post-earthquake functionality of the structure, as was the case in the hospital building during the Northridge earthquake highlighted above. Using storey loss functions from the toolbox developed by Shahnazaryan et al.,[38] however, can overcome some of these limits when estimating economic losses if the inter-element DS dependencies are defined. For example, damage to the furnishing of a hospital floor can be triggered not by their own fragility function, but by a certain level of damage in the water piping system located nearby, similar to the case reported by Chavez and Binder.[35]

2.3.4 | Quality of workmanship during installation

Another issue is the quality of the workmanship used to install experimental test specimens in a laboratory setting versus the quality encountered in reality. The representativeness of these specimens is debatable since a contractor constructing a few experimental NSE specimens that will be scrutinised heavily will likely give them more attention than usual. This is compared to the same contractor who could install dozens of these NSEs in practice with less attention to detail. This is not to say the contractor is providing sub-standard work in practice. The work is probably still more than acceptable for construction standards; it is the test specimens that are likely to be of excellent quality. The PACT library of fragility functions[16] does make some distinctions in this regard, where some indication of the seismic installation conditions can be specified for each NSE fragility function set, but no general guidance is outlined.

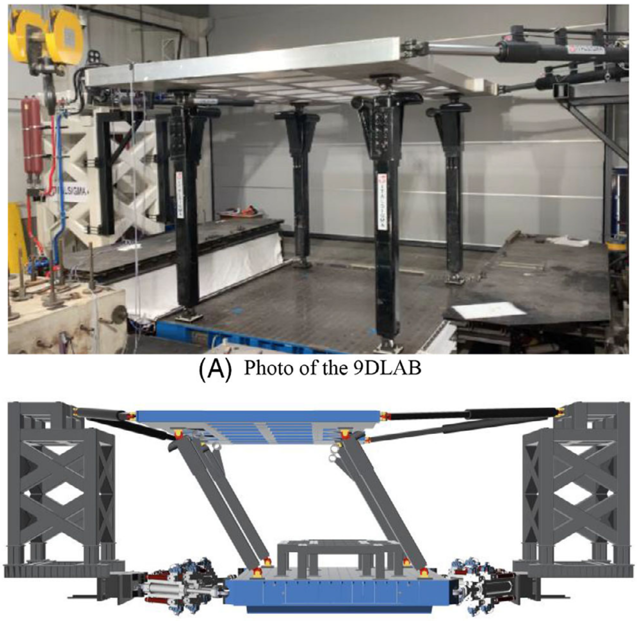
2.3.5 | Wear, tear and unanticipated interventions

Another important aspect to consider is that NSEs are typically elements that building occupants interact with and utilise regularly. Hence it is expected that a door or window that has been repeatedly opened for years may not have the exact same characteristics when tested as pristine in a laboratory. It could be argued that their continued use slightly wears down connections and movable interfaces, proving more space and flexibility to accommodate slight movements, which could possibly make them more resilient to seismic damage. Likewise, piping systems that have been in use, or had some general maintenance performed, may behave slightly differently. Also, there may have been some unanticipated interventions that change the characteristics of the NSE. For example, a piping system may have had its bracing configuration changed. A hole may have been made in a partition to allow some other element to pass through, or the type of glass used in the windows may have been replaced with a more thermally efficient one. Also worth noting are instances where cumulative cycles from past low intensity earthquakes have slightly damaged the NSE, but not enough to be characterised as actual damage worthy of repair. These are fine details that may seem trivial for what concerns seismic damage assessment. However, since the details have been repeatedly noted to make a difference in NSE behaviour, it is worth noting these issues nonetheless.

2.4 | Possible solutions to develop more representative NSE fragility functions

The issues highlighted in the previous section are issues known to many and generally accepted as contributors to the overall uncertainty. For example, when developing fragility functions, FEMA P-58 notes "*This uncertainty is the result of variability in the quality of construction and installation of components in a building, as well as variability in the loading history that a component might experience before it fails*". The same document goes on to recommend that in addition to the fragility function developed directly from experimental testing, some adjustments ought to be made depending on specific criteria. This involves increasing the dispersion value β of the fragility function through a square-root-sum-of-squares approach. For example, a value of 0.25 should be used if fewer than five specimens were tested, or if the NSE can be installed in several different configurations in an actual building, but all specimens were tested with the same configuration. The issue with this is that while it recognises the role of these factors in fragility function estimation, as noted in the previous section, it provides an arguably rudimentary way of accounting for them. It assumes that just the uncertainty value increases with no reduction in the fragility function's median η. Given the issues highlighted in Section 1.3, it would be reasonable to expect the NSE fragility to be somewhat more vulnerable (i.e., lower median value) and not only more uncertain (i.e., increased dispersion value).

While the issues highlighted in Section 1.3 have illustrated areas in which experimental data for NSEs may not be the best representation of reality due to the inherent setups of laboratories, there are some examples of this being addressed. Experimental testing at the E-Defense shaking table in Japan has seen some research programmes construct and test entire buildings, installing NSEs within them as they would be in reality, as opposed to just testing the structural system. Nakashima et al.[39] provided an overview of these activities, whereas Nagae et al.,[40] for example, described the testing of several NSEs within a two-storey frame structure equipped with curtain walls, ceiling systems and several types of office contents that were damaged. While constructing an entire structure followed by installing NSEs can be costly to conduct, recent advancements in laboratory testing facilities to mimic reality as closely as possible have been specifically developed for NSEs. For example, the Non-structural Component Simulator at the University of Buffalo[41] can simulate demands experienced by NSEs in a single direction on more than one storey level and has been used for several test campaigns. Also, the 9DLAB shaking table at the Eucentre Foundation in Italy (Figure 3) provides a means of acceleration input on specimens at two separate elevations in a total of nine degrees of freedom (i.e., six on the lower table, three on the upper),



(A) Photo of the 9DLAB

(B) Illustration of the 9DLAB in action

FIGURE 3 Illustrations of the 9DLAB at the Eucentre foundation to experimentally mimic realistic demands on NSEs.

mimicking the imposed loading on NSEs of two adjacent floor levels in a much more realistic manner compared to just base input. This also allows for different NSEs to be collectively installed and to examine their possible interaction[1].

Another solution to developing fragility functions that may address many of the issues highlighted in Section 1.3 would be to collect information from actual NSEs installed in situ or to perform tests on components extracted from the in-opera condition as done with structural elements. This presents many difficulties since performing in situ tests on NSEs may not be so straightforward; for example, how would the structure be excited enough to damage NSEs without causing concern to the occupants, or even damage to the structure? Alternatively, the damage observed during past earthquakes can provide a valuable means, but the obvious problem is the systematic and standardised collection of reliable data to permit this.

In Japan, such a system has been under development for many years. While SHM began in Japan in the 1950s, the number of instrumented buildings was in the range of 150 before 2011.[42] Given the urgent need to inspect a vast number of buildings in the Tokyo metropolitan area following the 2011 Tohoku earthquake, SHM was seen as a better means to promptly assess building safety in future earthquakes. Kanda et al.[42] describe how building SHMs in Japan was developed as a result of this need and how it has seen a steady increase in implementation since 2011. They report that around 500 buildings were instrumented as of 2016, around 850 as of 2018, and that these numbers continue to rise. They also reported the experience with their SHM system named q-NAVI, which has been deployed in over 500 buildings (as of 2021) in various parts of Japan. The q-NAVI system was used to provide a means to quickly and reliably assess the safety of many buildings, allowing occupants to return to their homes instead of waiting for an engineer to arrive, but it also has enormous potential to provide in-situ data on NSE demands. Since its widespread deployment in 2015, it has recorded vast amounts of data from the 2018 Osaka and 2018 Hokkaido Eastern Iburi earthquakes. Ogasawara et al.[43] provide a tentative comparison of the data obtained during the 2018 Osaka event from the q-NAVI system and the reported damage observations following the actual building inspections. The SHM records floor accelerations at the floor slabs meaning that the peak values of storey drift can be obtained through integration. Combined with the actual observations reported by the post-earthquake surveys, this type of data could prove to be a valuable resource for estimating more accurate NSE fragility functions that overcome many of the limitations discussed in Section 1.3. It is important to note that these observations and data collected and discussed herein refer primarily to commercial buildings and their associated NSE typologies, and extension to other situations should be dealt with accordingly.

[1] https://www.youtube.com/watch?v = cHKkc5LhPoc

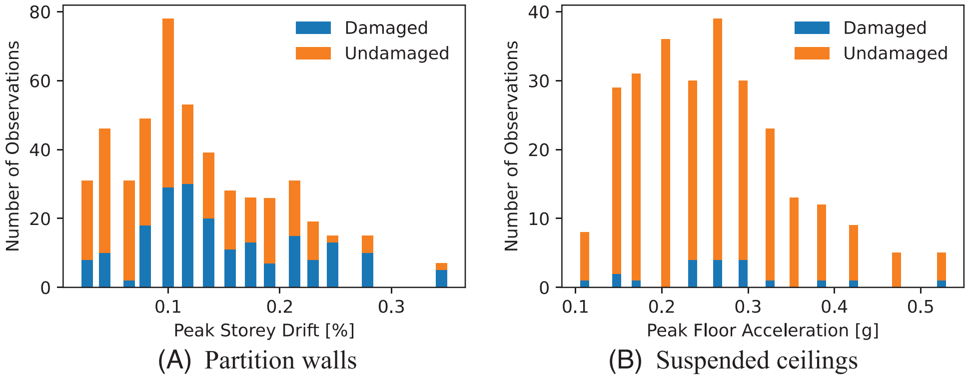


FIGURE 4 Binned distribution of damage observed following the 2018 Osaka earthquake.

2.5 | SHM data for improved NSE fragility functions

While the data collected from SHM systems like q-NAVI has clear potential, it is essential to investigate how it can be transformed into something usable for NSE fragility function development and improvement. One of the main difficulties involved in fragility function development using data collected from SHM coupled with post-earthquake inspection reports is the format of the data obtained. For example, during a well-instrumented experimental test on a particular NSE where a quasi-static protocol is applied [e.g., ref. 26], several specimens may be tested and the precise value of EDP at which each DS occurs can be noted. Knowing the EDP value that induced a certain DS in the specimens, the fragility function may be fitted (Method A as per Porter et al.[18]) via the method of moments. However, data obtained from SHM and post-earthquake reports will simply provide a list of observed maximum EDPs and the DSs of each NSE present. The key difference is that this EDP value is the maximum observed value, not necessarily the actual EDP at which the DS was induced. To tackle this kind of data, Porter et al.[18] described an alternative Method B by using bounding data.

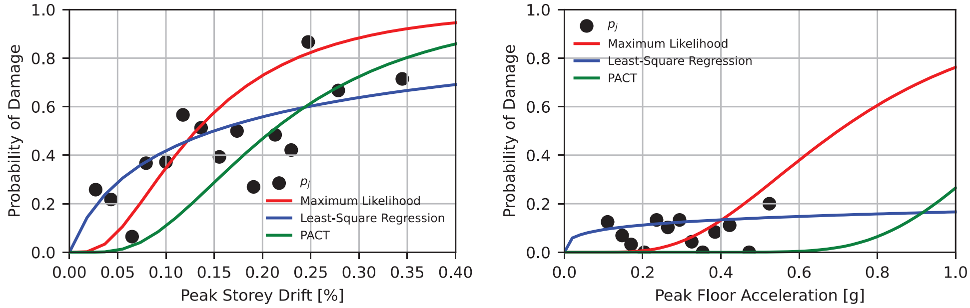
As a means of illustration, data collected by Ogasawara et al.[43] on 26 buildings surveyed following the 2018 Osaka earthquake is used here to develop fragility functions and provide commentary. All buildings were office buildings between seven and twenty storeys high, all constructed between 1974 and 2009, and no significant structural damage was reported for any of them. The q-NAVI system provided data on the maximum observed demands, but it was necessary to survey the damage to make the structures usable. Characterisation of the damage was based primarily on interviews with building managers that were conducted about 2 months after the earthquake. Photos taken immediately after the earthquake were used to confirm any damage already repaired. It encompasses eight different NSE typologies described in Ogasawara et al.,[43] but detailed information was only available for the partition walls and suspended ceilings as these sustained the most significant damage. The survey data was collected in binary format (i.e., the NSE was damaged or not damaged); however, future survey work may look to differentiate further the degree of damage on each NSE (i.e., light, medium, extensive etc.).

From the damage data obtained for partition walls in both orthogonal directions of the buildings, a total of 494 observations were recorded. This data were binned and is illustrated in Figure 4(A). For the ceiling damage data, a total of 270 observations were recorded and the binned data are illustrated in Figure 4(B). It is clear that partition walls had many more instances of damage compared to the suspended ceilings.

With such information at hand, the next step is to build fragility functions. The key advantage of such fragility functions is that they are built using data recorded from NSEs installed in their actual conditions subjected to actual earthquake-induced forces and deformations. Recalling the various limitations discussed in Section 1.3 when developing fragility functions based on experimental data developed in a laboratory setting, the possible advantages offered by SHM should be clear.

To develop fragility functions with SHM data in this format, Method B described by Porter et al.[18] was implemented, as per FEMA P-58. The data were separated into several bins, illustrated in Figure 4. Porter et al.[18] go on to describe how this can be used to obtain an estimate of the probability of damage in each bin p_j as:

$$p_j = \frac{m_j + 1}{M_j + 1} \tag{2}$$



(A) Partition walls: fitted function $\{\eta = 0.13\%, \beta = 0.69\}$ and first DS for wall partition components (C3011.001a) in PACT

(B) Suspended ceilings: fitted function $\{\eta = 0.71\text{g}, \beta = 0.50\}$ and first DS for suspended ceilings (C3032.001a) in PACT

FIGURE 5 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.

where m_j is the number of damage observations in bin j, M_j is the total number of observations in bin j and adding 1 to both is to avoid computational issues when $m_j = 0$. Equation (2) is essentially an empirical estimate of the left-hand side of Equation (1) for EDP $= edp_j$, which is the bin's average EDP value. Porter et al.[18] then describe how substituting in p_j and taking the inverse Gaussian distribution of both sides of Equation (1) gives:

$$\Phi^{-1}\ (p_j) = \frac{\ln\left(\frac{edp_j}{\eta}\right)}{\beta} \tag{3}$$

$$\Phi^{-1}\ (p_j) = \frac{\ln\left(edp_j\right)}{\beta} - \frac{\ln(\eta)}{\beta} \tag{4}$$

which when rearranging to the equation of a line $y = ax + b$, where $y = \Phi^{-1}(p_j)$ and $x = \ln(edp_j)$, the median and dispersion can be found by simple least-square regression to give:

$$\eta\ = \exp\left(-\frac{b}{a}\right) \tag{5}$$

$$\beta\ = \frac{1}{a} \tag{6}$$

Applying this method to the data shown in Figure 4 resulted in very poor fits to the data, as illustrated in Figure 5. It can be seen that the fitting follows the available data closely, but fails to recognise that the data are truncated, and more data would bring the general trend back towards what one may expect. This is obvious from the abnormally high probability estimates at low demand levels.

Other methods for fitting fragility functions using limited data have also been discussed by Baker,[44] with the most notable being the maximum likelihood estimation approach to be used in the context of seismic fragility function development. Here, instead of fitting a least-squares pair of fragility parameters, the likelihood of the fitted distribution being able to reproduce the observed data are instead maximised through Equation (7):

$$\{\eta, \beta\} = \underset{\eta,\beta}{\text{argmax}} \sum_{j=1}^{N} \left[\ln\begin{pmatrix} M_j \\ m_j \end{pmatrix} + m_j \ln\Phi\left(\frac{\ln\left(\frac{edp_j}{\eta}\right)}{\beta}\right) + \left(M_j - m_j\right)\ln\left(1 - \Phi\left(\frac{\ln\left(\frac{edp_j}{\eta}\right)}{\beta}\right)\right)\right] \tag{7}$$

Applying this approach to the same data gives the fragility function shown in Figure 5, where it can be seen that the fitting with respect to the observed data are much improved. In fact, Baker[44] discusses the use of Porter et al.[18]'s Method B and notes that applying it in this context ignores the non-uniform variance of the data, violating the requirements of least-square regression fitting. Like Figure 5, Baker[44] noted that this tended to produce very high probabilities at very low demand levels, which is quite unlikely and counterintuitive. This is especially true for the fragility function fitted for ceilings in Figure 5(B), where the probability of damage is essentially constant for all demand levels. Maximum likelihood fitting, on the other hand, was shown to be much better at representing the overall trend of the data. It should be noted, however, that the SHM data does, in fact, violate a basic assumption of the maximum likelihood fitting: the observations in different bins are independent. Given that the SHM data comes from few earthquakes on limited number of buildings, it is likely that there is non-independent data in several bins. This aspect is not discussed further here, but interested readers are referred to Straub and Der Kiureghian[45] for further reading on the topic.

While the discussion on Figure 5 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 discussion in Section 1.3, 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 5. 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. While this is a preliminary observation based on a reasonably large dataset, it shows that much of the discussion in Section 1.3 holds some merit when compared to actual field observations. Many of the points argued in Section 1.3 were based primarily on considerations made by the authors following further scrutiny and processing of the SHM data, but also based on the numerous minor observations and comments that many researchers in countless NSE experimental test campaigns throughout the years have made. The main point to take away from this discussion is that SHM from systems such as q-NAVI can complement experimental data and provide a valuable source for an improved means to estimate fragility functions for damage to NSEs.

3 | ROLE OF NSES IN THE REPAIR AND RECOVERY OF BUILDINGS

The previous section discussed using fragility functions to estimate NSE damage during earthquakes. It noted the difficulties in ensuring these functions are as representative as possible compared to actual observations, where data from some notable Japanese earthquakes were examined. This section changes its focus to discuss not just how to estimate damage to different kinds of NSEs, but their general role and importance for building repair and recovery. The role of NSEs in economic losses and the post-earthquake functionality of buildings are discussed with reference to recent experiences in Japan, and some potential avenues for future research and guidelines are explored. It is important to underline that the discussions presented here principally relate to the repair cost implications that building owners are typically faced with, and not necessarily issues relate to emergency management.

3.1 | Prominence in monetary value and repair costs

In recent decades, seismic engineers have increasingly accepted that NSEs are crucial in overall building performance. This stems back to observations made as early as the 1920s by Engle,[1] who noted that a building allowing extensive damage to its NSEs, like partitions and finishes, is of little use post-earthquake, even if it has avoided structural collapse. Focusing attention solely on the building frame was considered illogical since the building frame cost rarely exceeds 15% of the total. Despite observations like this being made almost 100 years ago, much of the research in the following decades focused on developing analysis methods and structural systems that could ensure life safety via ductile mechanisms. For example, Megget[46] provided an overview of the developments of ductile seismic design in New Zealand over a period of 75 years, where the focus was on how engineers managed to move from brittle systems to more ductile and resilient structural design concepts widely adopted nowadays. Similarly, Fajfar[47] gave an overview of the evolution of seismic analysis methods in earthquake engineering worldwide in the past 100 years, with analysis focused on structural response and some mention of anticipated non-structural performance in ATC 3-06.[48] Note that these examples are not intended to be a thorough review of guidelines addressing NSE performance, but rather an indication of the focus on structural analysis and design methods during this period. Further details on NSE guideline development may be found in Filiatrault et al.,[3] for example.

These early observations by Engle[1] regarding NSEs and their relative monetary value were restated and largely popularised by Taghavi and Miranda[2] on the monetary investments needed for office, hotel and hospital buildings disaggregated in terms of structural, non-structural and building contents contributions. This simple illustration (Figure 6) gave a clear indication of what had been commented on years earlier and laid the foundation for a more integrated consideration of

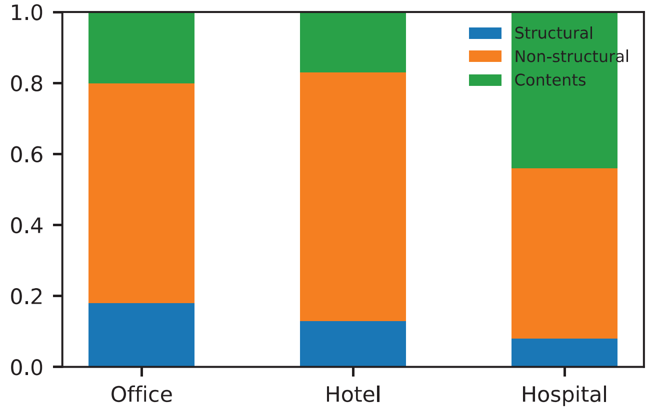


FIGURE 6 Cost breakdown of typical buildings in the US.[2]

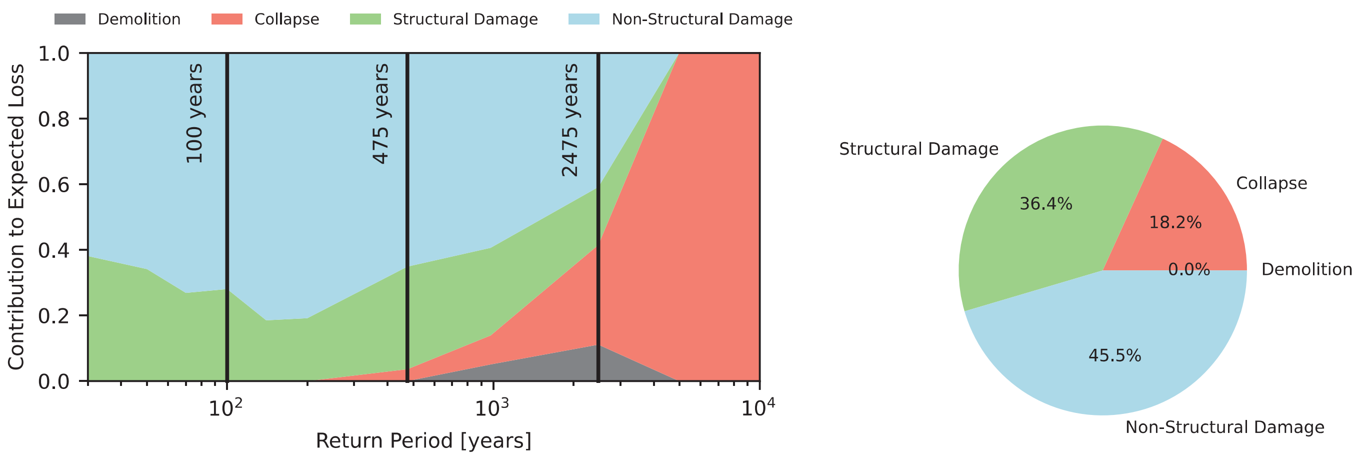


FIGURE 7 Illustration of the relative contribution to (left) the expected loss versus the return period of ground shaking and (right) to the EAL.[49]

the potential impacts of NSEs on building performance. Similar observations have been reported by Dhakal et al.[24] for New Zealand in recent years also.

This observation of the NSEs playing a prominent role in the initial financial investment of a building was also illustrated differently via the relative contribution to the repair costs required to fully rehabilitate a school building for increasing levels of ground shaking. O'Reilly et al.[49] showed that for more frequent and lower return period earthquake events, the contributions to the economic losses were dominated by the NSEs. Only at return periods associated with much stronger shaking did the contributions from the structural damage and the possible need to demolish and replace the building because of excessive residual deformation or collapse become more notable. This data, developed based on surveys and instrumentation of an existing school building in central Italy,[49,50] is shown in Figure 7 (left), where NSEs clearly dominate the percentage contributions to the economic losses until around a return period of 900 years, where their contribution is around 60%. While this is not the same kind of data presented in Taghavi and Miranda,[2] it essentially points to the same conclusion that a large percentage of the financial outlay depends on the NSEs, whether it is in the case of initial construction or repair activities.

It is recalled that a building's vulnerability curve (i.e., economic loss vs. seismic intensity) is developed using contributions from the collapse and non-collapse scenarios analysed during loss assessment, in addition to a usually relatively minor contribution due to the possible demolition because of excessive residual deformations. Knowing this vulnerability curve and the site hazard curve, the two can be integrated to compute the structure's expected annual loss (EAL). This was computed by O'Reilly et al.[49] to be 0.11% for the specific case study analysis, but the relative contribution of each group is shown in Figure 7 (right), which is of more interest to the present discussion. It is clear what had generally been discussed in past studies regarding the importance of NSEs, with their contribution to EAL being over 45%. This is because damage to NSEs predominately occurs during more frequent events, and when integrated over the expected rate of exceeding these intensities (i.e., how often these shaking events are expected to happen), they essentially dominate the EAL.

Many different research groups have reached similar conclusions and observations for different structural typologies worldwide. For example, Arnold[51] noted in the early 1990s that if the current seismic code philosophy persists, there will continue to be non-structural damage, specifically significant disruption to contents. Silva et al.[52] noted that steel buildings designed to Eurocode 8 tended to exhibit a good margin of safety against collapse but that notable losses resulted from damage to the NSEs at low intensities. Hwang and Lignos[53] also reported the same observations for steel moment-frame structures design following US provisions. Baradaran Shoraka et al.[54] showed that non-ductile reinforced concrete (RC) located in California tended to have their losses dominated by NSE damage repair costs. O'Reilly and Sullivan[55] observed the same results for non-ductile RC frame buildings with masonry infills in Italy. Coupling this with the countless observations of NSE damage reported in past earthquakes[3,34,36,56] and the estimated costs of repairing this observed damage, this has led to the now well-established notion that the seismic performance and resilience of buildings is primarily dictated by how resilient its NSEs are when life safety is not a significant issue.

This impact of NSEs on monetary losses is especially noteworthy since EAL has gained much attention as a metric to quantify and classify seismic risk. This is seen through the introduction of the Sismabonus guidelines in Italy in 2017[57–59] where buildings owners can obtain tax rebates on the cost of interventions to increase building safety through upgrading their seismic risk rating by a prescribed amount. This seismic risk rating is the more critical of a life safety index and an EAL rating; hence, when life safety is not an issue, the expected losses are the primary driver of these interventions. This EAL parameter also feeds into the reinsurance industry[60] as a parameter indicating the financial loss one would expect annually because of the building's current condition and the seismic hazard it is exposed to. These kinds of observations have undoubtedly sparked a keen interest in the earthquake engineering community worldwide; if the losses are being dominated by NSEs in structures that are relatively modern and not at significant risk of collapse, then it follows that efforts should be focused there.[61] This may be via NSE solutions that better resist damage or prevent many failures repeatedly observed during past events. The relative value and cost of repairing each NSE with respect to each other[62] can also be used to indicate where the most significant benefit in EAL reduction may be achieved for a given NSE-based intervention scheme.

3.2 | Recent Japanese experiences

The previous section has highlighted some of the research efforts made over the past decades to raise awareness of the importance of issues beyond structural collapse and life safety, with the repair costs associated with NSEs becoming a notable issue now receiving much more attention. This section focuses on recent Japanese earthquakes to examine how some of these research conclusions compare with actual observations following strong shaking. This is discussed with reference to the 2018 Osaka and the 2018 Hokkaido Eastern Iburi earthquakes, which have been examined in detail using the q-NAVI system.[42] Much data on structural and non-structural damage were collected following these events, as mentioned in Section 1.5. Also of great value are the numerous interviews and reports on the actual impacts on the building's functionality. As previously mentioned in Section 2.4, these data and observation were collected for commercial buildings with typical office-type NSEs. This is important to note since it means that the entire building would have one centralised owner who makes the decisions on what actions to take. This differs to the case of a residential building, also comprising several individual units, but with the key difference that each unit is likely owned by its respective occupant or landlord. This means that the entire building is likely not owned by a singular entity that would facilitate decision-making on a more holistic scale.

As previously mentioned in Section 1.5, many buildings equipped with q-NAVI in recent years have sustained significant levels of ground shaking of MMS = VI, VIII and IX. Kanda et al.[42] reports that the q-NAVI noted no significant structural damage during the 2018 Osaka earthquake, but many buildings suffered damage to their NSEs. These included cracks to the gypsum partition walls examined in Section 1.5, water leakages from piping, the collapse of some tiles of a suspended ceiling system, and the failure of some mechanical devices, which can be deemed representative of a wide variety of NSE typologies (i.e., drift vs. acceleration sensitive, fixtures and fittings vs. mechanical services). While the NSE damage was at times notable in buildings, the building maintenance managers, both on-site and at the headquarters, and eventually building owners concluded that this NSE damage was not such a critical issue after all. They found that in many instances, the damage to many NSEs can be tolerable in both the short and long-term operation of the building's primary function, avoiding any major panic on high repair costs and financial losses that many analytical studies, such as those outlined in Section 2.1, have tended to points to. For example, diagonal cracking in gypsum partitions was widely observed in many buildings. This is a relatively minor damage mechanism but its repair costs implications when strictly following the FEMA P-58 framework[16] can be significant. Partitions would need to be replaced throughout the building, and a complete repainting and redecorating process would need to be completed, causing disruption and likely at a high price given the scarcity of materials and labour in the immediate aftermath of an earthquake. What was found in many cases was that, yes, the damage mechanism did appear alarming to occupants in the initial aftermath of the earthquake, but after a couple of days it was not really of much concern in the broader perspective. Occupants tended to view the damage pattern as just another ornament or picture on the wall to observe with amusement. This stemmed from the occupants' desire to initially clean up and repair minor damage via ad hoc measures to get back to "*business as usual*" once the building had been declared safe. It is noted that the composed response of occupants in Japan can be largely credited to earthquake safety education, awareness programmes, and widespread earthquake exposure, the behaviour of individuals in different countries can vary significantly due to differences in earthquake information dissemination, preparedness levels, and exposure. Another example observed was doors jamming due to the distortion experienced during seismic shaking. Unless the jamming was serious and prevented access or egress to and from important areas of the building, it was just dealt with via some additional force or just left open. In many cases, building owners just opted to wait until the next refurbishment cycle to address these issues, as there was no major panic.

These two examples point to field observations of NSE damage that was not of much concern to the building's actual functionality. However, there were some specific instances in which building managers did raise issues concerning NSE damage and the building's post-earthquake function. These were related to water-related damage, failure of essential mechanical services and the dislocation and/or partial collapse of tiles in exterior claddings. The water-related damage involved burst pipes that flooded specific areas meaning the damage could not be immediately swept up and addressed by regular occupants. It instead required the replacement of many items and furnishings damaged by the leakage and the piping system itself. This exact NSE damage mechanism has also been observed in past earthquakes in the US,[51] Japan[37] and Chile,[36] for example, as noted in Section 1.3.3. The failure of mechanical services is principally related to the operation of air-conditioning and heating systems essential during both summer and winter months. The issues related to the dislocation of exterior cladding, although seldom reported, were due to concerns for the pedestrian and building occupants' safety. This kind of damage was addressed urgently, often at a premium cost due to the aforementioned issues of labour and material shortages, in addition to the price surges that can follow such earthquake events.

Overall, from these earthquakes of relatively intense shaking in Japan, for which much data and field reports were gathered for conventional non-isolated RC structure, the general conclusion was that NSE performance was mostly not of major concern for these building typologies. This is contrary to much research into specific NSE issues and their relative contribution to monetary losses previously discussed. Granted, some specific NSEs did create issues in some instances but the general damage reported to NSEs was not of significant concern in most cases.

3.3 | Relative importance for recovery

Given the observations in the data collected in Japan regarding the actual impact of NSE on commercial building functionality, the question arises as to how useful the repair costs and loss estimates traditionally used in methodologies such as those outlined in FEMA P-58 and widely adopted in the literature actually are? Analytical studies have shown that the NSE repair costs can represent the large majority of the total (Figure 7), whereas actual observations indicate this may be an overstatement. Traditionally, code-conforming buildings worldwide aim to ensure life safety and limit damage to structural and non-structural elements. In the past, loss assessments have primarily aimed to achieve complete recovery or to repair and restore buildings to their pre-earthquake condition, sometimes with additional improvements. This implies that the building manager must take care of every single partition wall crack and ceiling tile before people set foot inside the building again. Studies such as Bonowitz[63] defined recovery states (RSs) that one may target; specifically, the re-occupancy, the functional recovery or the full recovery of a building, which represent compromises on a full recovery. As part of efforts to improve the estimation of downtime and model the overall recovery process of buildings, the REDi rating system described by Almufti and Willford[64] explored the notion that for a building to regain its functionality, a series of key repair action sequences should be following to gradually return a building to some fraction of its previous functionality level. It begins to break down the recovery process into a series of steps that must be followed and can also be quantified. These concepts have been furthered by Molina Hutt et al.[65,66] who scrutinised the repair sequences and how

TABLE 1 Recovery states addressed by different building recovery frameworks.

Recovery state	FEMA P-58	REDi	Molina Hutt et al. (2022)
Full recovery (RS1)	X	X	X
Functional recovery (RS2)		X	X
Re-occupancy (RS3)		X	X
Shelter-in-place (RS4)			X
Stability (RS5)			X

works may be optimised to provide more representative estimates of downtime while considering issues like impeding factors, sequencing of repairs, and more importantly for the current discussion, the expected RS of the building.

Considering these discussions regarding recovery and how decision-makers are now applying a more rational approach to estimating recovery times, it is proposed that a similar line of thinking should be applied to economic loss computation. As described in Molina Hutt et al.,[65] the FEMA P-58 methodology works on the assumption of full recovery, meaning that every single damaged item should be repaired before the building is considered functional (i.e., each cracked partition replaced and each door repaired). As field reports have shown, this is not quite the case and building managers and occupants have a good degree of tolerance depending on the situation. This kind of tolerance, or differentiation of what is essential to repair and what can be lived without, was developed into the notion of RSs by the REDi rating system[64] and again furthered by Molina Hutt et al.[66] Molina Hutt et al.[66] described five RSs ranging from 'full recovery' to 'stability', which are shown in Table 1 with respect to the REDi rating system and FEMA P-58. To make the estimates of economic losses more representative of reality, these concepts of RS should be incorporated, and the anticipated RS should also be stated when conducting a loss assessment. This essentially means scrutinising the building's damageable inventory into what is and is not required for a given RS to be achieved. It involves examining each damageable component's DSs individually and deciding what RS would be lost for this level of damage. In essence, the building's damageable inventory used in FEMA P-58 and other methodologies[67] is reduced depending on what is and is not essential to repair for a given RS. For example, referring to the case of partition wall damage in Japan, these initial DSs indicating minor damage would not be required for achieving 'functional recovery' according to Table 1. Consequently, these could be omitted from the loss assessment. However, damage to the water pipe would be necessary for "functional recovery" and needs to be included in the assessment.

3.4 | Case study application

To illustrate how this kind of differentiation could be applied in practice, a short case study example is presented. The building is a four-storey RC frame structure previously analysed by Shahnazaryan et al.[68] It was designed following the Eurocode 8 design provisions[69] for a site in L'Aquila, Italy. The material properties used in the design and detailing were 25 MPa for the concrete compressive strength and 415 MPa for the steel yield strength. No plan or elevation irregularities were considered. The structure was modelled using OpenSees[70] as a single planar structure for simplicity. The masses were lumped at each floor and the nodes were constrained horizontally to mimic a rigid diaphragm behaviour. A concentrated plasticity approach was used to model non-linear behaviour in beams and columns, while the elastic sections of the elements were modelled using an elastic cracked section stiffness. To obtain the hysteretic models, the backbone curve associated with each structural element was fitted to a moment-curvature relationship of the element, and the plastic hinge length required for the hysteretic model was computed following Priestley et al.[71] All columns were fixed at the base and a Rayleigh damping model with 5% of critical damping was implemented. P-Delta effects were considered by applying vertical gravity loads to a leaning column during non-linear analysis. Beam-column joints were assumed to be rigid, and no shear mechanisms were modelled since the design followed capacity design criteria.

The building was analysed using incremental dynamic analysis[72] and the losses were computed using the storey loss function-based approach described in Shahnazaryan et al.[38] The complete damageable inventory adopted in the loss assessment was taken from the original study by Shahnazaryan et al.[68] and is listed in the first column of Table A1 (see attached supplement). Details on quantities, assumed repair costs and fragility function parameters are omitted here as they may be found in the original study and are not directly relevant to the current discussion. To incorporate the notions outlined in Table 1, each DS for both structural and non-structural damageable components was assigned an RS. If a DS

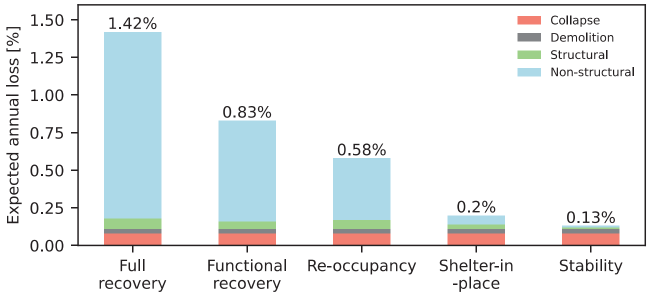


FIGURE 8 Expected annual loss results as a function of the RS targeted.

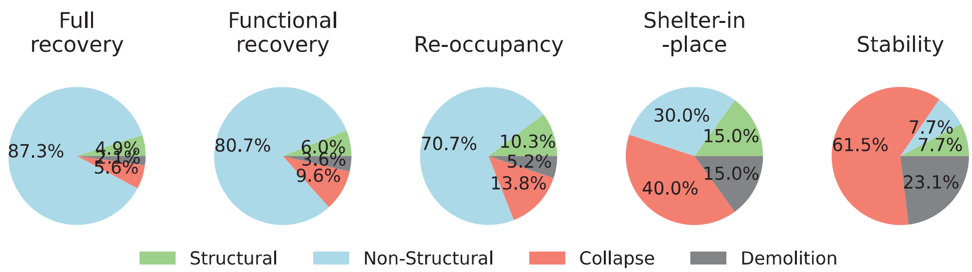


FIGURE 9 Relative contribution to the EAL for each RS.

occurs, the building would no longer be considered in that RS until repairs are completed. For example, the structural elements (i.e., beams and columns of the structural system) were assigned an RS of 'stability' (i.e., RS5) for their most severe DS comprising fracturing of rebar and spalling of concrete, since this DS would not permit the 'stability' RS of the building. Likewise for the internal partitions, whose first two DSs are assigned an RS of 'full recovery' (i.e., RS1) since their description describes light damage that could be tolerated in other RSs but not when full recovery is expected.

To utilise this table and conduct a loss assessment with it, only specific elements and DSs need to be considered depending on the RS under examination. For example, if 'full recovery' is targeted, then all DSs assigned RS1 or higher should be included, whereas if 'functional recovery' is targeted, then DSs assigned RS2 or higher are included in the damageable inventory. This would mean that the initial DSs of the internal partitions and other components like internal doors and bookshelves are excluded from the loss estimate. This essentially means excluding many DSs for components, that could be tolerated based on the decision-maker's preferences.

A loss assessment was carried out for the building depending on the target RS, and the results in terms of the EAL are shown in Figure 8. By first examining the 'full recovery' state, which is what has been assumed until now in guidelines like FEMA P-58 and past studies by O'Reilly et al.,[49] an EAL of 1.42% was found, with the vast majority of the losses arising from the repair of the NSEs. The absolute value of the EAL is not of concern here as this depends on the structure under examination, site hazard and also the damageable inventory composition. Examining the 'full recovery' state, it is generally in line with the previous analytical observations discussed in Section 2.1, where NSEs played a vital role. However, when the damageable inventory used to conduct such a loss assessment is revised to consider only the repairs that would be strictly necessary to achieve an RS not of 'full recovery' but of 'functional recovery' or even 're-occupancy', whose more complete description and assumptions are available in Molina Hutt et al. (2022), Figure 8 shows that the EAL quickly drops to 0.83% and 0.58%, respectively, representing a 42% and 60% drop in the EAL. This is primarily because the NSEs that are not needed for these RSs are no longer inflating the loss estimates and expected repair costs for issues that can be simply accepted, as was seen in Japan. Figure 9 shows the relative contribution to the loss, where it can be seen that when RSs other than 'full recovery' are targeted, the NSE contribution becomes less and less pronounced. This is also supported by the repair cost data collected by Yoshizawa et al.[37] following the 2011 Tohoku earthquake for an RC frame office building, who noted that around 56% of the costs were associated with the architectural components.

The presented case study and related discussions demonstrate a more refined method for assessing losses. This refinement eliminates the implicit assumption of a 'full recovery', providing decision-makers with a clear understanding of their expected RS for a given EAL value and the biggest contributors to this EAL. This prevents non-critical components from being unnecessarily addressed or prioritised during proactive retrofitting measures, avoiding the waste of financial resources to achieve 'full recovery' when many building owners and occupants would deem 'functional recovery' a sufficient RS. This aligns with recent observations in commercial buildings in Japan after earthquakes, where addressing light diagonal cracking in gypsum partitions is necessary for 'full recovery', but not for 'functional recovery', thus shifting the priority to other elements, as shown in Figure 9. The implicit assumption that the life safety of the occupants is not a threat still remains a priority, however, and steps to ensure a sufficient margin of safety against collapse should take priority over refinements to the expected monetary losses. The focus here is on direct economic losses and financial investment, although much of the discussions here regarding RSs and building functionality form part of a broader discourse on downtime and interruption that can be used to estimate indirect losses and other consequences.

On a more general note, when discussing recovery after an earthquake, it's important to consider prioritising what is essential versus non-essential. This can indirectly address issues of price surges and inflation due to increased demand and a limited supply of materials and labour. By adopting the concepts discussed and presented here, building owners can choose to focus on a 'functional recovery' rather than a 'full recovery' by not addressing non-essential repairs right after an earthquake, as they may be more costly to fix during the immediate aftermath. This mainly applies to buildings where a centralised ownership and decision-making framework exists, facilitating a more holistic approach to post-earthquake recovery, and may be more difficult in residential building situations where several owners and consequently decision-makers exist and would need to align. Waiting until demand and prices have subsided could be a more prudent approach. Again, this is essentially what building owners in Japan chose when they simply opted to address minor NSE damage in the next scheduled refurbishment cycle, rather than addressing it immediately and paying a premium price for it.

4 | SUMMARY AND CONCLUSIONS

This paper has discussed several pertinent issues regarding estimating damage to non-structural elements (NSEs) in earthquakes and the related consequences that may be expected on a more general level of performance. It has used several observations from commercial buildings in recent Japanese earthquakes to provide helpful insight and discussion on the reality observed in many cases and compared this to the recent developments in research within the scientific community. This is related to the estimation of damage via fragility functions and how recent initiatives on structural health monitoring (SHM) can be used not only to monitor and assess structural safety following a major seismic event, but it can also be the source of very useful data for representative fragility functions used to estimate damage. Similarly, the observation and conclusions reached by many building managers and owners in Japan regarding tolerable damage provide helpful insight into the acceptance of functional recovery and states other than a full and immediate recovery of the building. Based on the discussions and examples provided, the following points can be concluded:

- Fragility functions are key to estimating damage to structural and non-structural elements in buildings; however, when specifically considering NSEs and the techniques often used to derive their fragility functions, there are many cases when these fragility functions may not be representative of what is generally encountered in reality. This was discussed to be either due to installation conditions and loading protocols used in experimental testing, the possible interaction with other elements, variability in the quality of workmanship and possible wear, tear and degradation. The potential impacts of these were highlighted and how they may adversely impact the performance of NSEs and the estimation of representative fragility function.
- SHM was discussed as the optimal approach to address this issue and to estimate more representative fragility functions for NSEs, especially when structural damage is not an immediate concern. Data from several buildings in Japan were collected and utilised to derive such fragility functions for partition walls and suspended ceilings. After comparing these fragility functions with those found in literature, it was confirmed that these NSEs may be more vulnerable when assessed using fragility functions that were derived from actual demand data from real buildings rather than ones that were experimentally derived and may not fully reflect the actual conditions.
- When analysing the data collected from several interviews with commercial building owners and managers following recent Japanese earthquakes, it was found that in many cases, minor damage to their NSE typologies was not such a critical issue to resolve immediately, especially during price and demand surges following major earthquake events. This appears to be contrary to the many studies in the literature that have highlighted the key role of NSEs in the economic impacts, such as initial investment and potential monetary losses and emphasised the need for their improved performance to increase overall resilience. What was deemed critical, however, were issues where the usability of the building had been comprised, generally due to water damage from damaged piping. It was discussed how these

observations from Japan are essentially field observations of what is generally termed functional recovery in the community; it represents a shift in focus from full recovery to some other lower, but still acceptable, level of recovery, depending on the building owners' and decision-makers' needs. A short case study example of how this could be incorporated into loss assessment was presented. The major observation is that when considering functional recovery or re-occupancy rather than full recovery typically assumed, the expected annual losses dropped by 42%–60% because of NSE repairs that were no longer immediately necessary. This suggests that a more prudent evaluation of the relative importance of different elements in a building should be sought when carrying out repair or retrofitting interventions and that the anticipated level of recovery should be clearly defined.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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