17th World Conference on Earthquake Engineering, 17WCEE

Sendai, Japan - September 13th to 18th 2020

A FRAMEWORK FOR THE SEISMIC RATING OF NON-STRUCTURAL ELEMENTS IN BUILDINGS

T.J. Sullivan(1), R.P. Dhakal(2), J. Stanway(3)

(1) *Professor, University of Canterbury, timothy.sullivan@canterbury.ac.nz*
(2) *Professor, University of Canterbury, rajesh.dhakal@canterbury.ac.nz*
(3) *Principal Structural Engineer, WSP-Opus, jan.stanway@wsp-opus.co.nz*

Abstract

Research into the seismic performance of non-structural elements over the past decade in New Zealand has identified a number of areas in which changes should be made. Gaps have been identified in the understanding of the seismic performance of different types of non-structural elements in existing buildings, and issues have also been noted with the design, procurement and installation processes used for non-structural elements in new buildings [1]. In response to this, it is proposed that non-structural elements be rated according to their drift and acceleration capacity. The rating system promises to (i) help engineers to correctly specify and detail non-structural elements for buildings of different importance levels in line with their expected performance in earthquakes, (ii) assist in communicating the performance expectations for all categories of non-structural elements, and (iii) help facilitate inspection and compliance checks for sign-off of non-structural elements. After describing the framework of the proposed rating system, the potential impact of its use is considered. The discussion suggests that a rating system for non-structural elements could lead to significant improvements in the seismic performance of buildings and thus should be considered further by the industry.

Keywords: non-structural elements; rating system; loss assessment; non-structural components

Introduction

The term "non-structural elements" can be used to refer to any elements in a building that do not have a structural function, and may include architectural components and cladding, mechanical and electrical services and even building contents. There appears to be increasing recognition in the earthquake engineering community that improved seismic performance of non-structural elements will be key to limiting the damage and disruption caused by earthquakes (Filiatrault and Sullivan, [2]). However, current design standards generally appear to have only limited information for checking of non-structural elements. Furthermore, there is an increasing body of evidence that a number of drift limits specified in codes will not lead to intended design outcomes.

Table 1 reports the median drift at which damage is first observed during experimental testing of a number of common non-structural components. To put these values in perspective, note that Priestley et al. [3] report that a typical value of storey drift at yield of a RC frames is around 1.0%, with higher yield drifts typically expected for steel MRFs. This underlines the notion that if non-structural elements with good seismic performance are not specified, damage can be expected at intensity levels significantly lower than those expected to cause damage to the structure. To this extent, note that Eurocode 8 does impose storey drift limits of 0.5% and 0.75% as a damage-limitation requirement for brittle and ductile non-structural elements respectively, with a 1.0% drift limit prescribed for the damage limitation state when non-structural elements are fixed in a way so as not to interfere with structural deformations. Given that the Eurocode 8 values are all higher than the capacities indicated in Table 1, it is apparent that the intensity at which damage occurs could again be significantly lower than the intensity levels that codes prescribe for design.

Table 1: Examples of storey drift capacity observed from experimental testing for a range of common drift-sensitive non-structural elements

Non-Structural Element Type	Median drift at which initial damage observed	Reference
Plasterboard partition walls	0.29%	Davies et al. [4]
Solid clay brick infill walls	0.14%	Sassun et al. [5]
Curtain wall glazing*	0.35%	Arifin et al. [6]

** Corresponding to loss of water tightness. Significantly higher values could be expected for different types of curtain wall glazing systems*

Table 2 reports median values of peak floor acceleration capacity for a selection of common acceleration-sensitive non-structural components. It is not as easy to gauge what these acceleration capacities would imply without first analyzing a structure and identifying the floor accelerations that result. However, it is understood that there is a trade-off between floor acceleration demands and drift demands; if the engineers specifies a stronger, stiffer structure to limit drifts then higher floor accelerations are likely to result and on the contrary, if a more flexible structural system is designed then storey drift demands will tend to be high but floor accelerations should be relatively low.

Table 2: Examples of peak floor acceleration (PFA) capacity observed for a range of common acceleration-sensitive non-structural elements

Non-Structural Element Type	Observed median PFA at which serviceability limit state exceeded	Reference
Unbraced suspended ceilings	0.6g - 1.2g	Soroushian [7]
Sprinkler piping systems	0.5g – 1.0g	Soroushian et al. [8]
Battery rack systems	1.17g	Ghith et al. [9]

Given the points made above, it is apparent that the likelihood of exceeding the drift and acceleration capacities indicated in Tables 1 and 2 above will depend not only on the intensity of ground motion shaking but also on the selected structural system (and other factors as well). To this extent, to achieve good seismic performance of non-structural elements, the engineer needs to be able to effectively communicate the drift and acceleration demands they anticipate for their specific building to any sub-contractors responsible for design and installation of non-structural elements. Alternatively, the engineer should be able to specify the required capacity of non-structural elements in different parts of a building. To facilitate such a communication process in New Zealand, this paper puts forward a seismic performance classification system for non-structural elements and considers potentials issues with its implementation.

Proposed classification system

To improve communication of performance requirements between engineers and sub-contractors, Tables 3 and 4 propose drift and peak floor acceleration (PFA) values, respectively, for the seismic classification of non-structural elements. A specific type of non-structural element would be classified according to its critical drift (or acceleration) capacity established relative to the two limits indicated for both limit states (noting that the ULS limits are only applicable to those non-structural elements for which failure would pose a life-safety threat). For example, if an element has an SLS drift capacity of 0.60% and a ULS drift capacity of 2.4%, it would be assigned Class D2 (SLS limit governs in this case). The intention of the classification system is to ensure that most components would automatically satisfy the lowest class rating without the need for conformance checks. However, comparing the drift limits indicated earlier in Table 1 with those of Table 3, it would appear that the class D1 limit would not be met by masonry infill walls. To this extent, the values proposed in Tables 3 and 4 are intended for use in New Zealand where masonry infill elements are not permitted without special detailing. As such, it is thought that the class D1 is a reasonable lower-bound limit.

Table 3: Tentative drift values proposed for the seismic classification of drift-sensitive non-structural elements in New Zealand

Non-Structural Element Class	Median Drift Capacity	
	SLS (No damage)	ULS (Life safety)*
D1	0.25%	0.75%
D2	0.50%	1.5%
D3	0.75%	2.0%
D4	1.00%	2.5%
D5	1.50%	3.0%

** only applicable to those non-structural elements for which failure would pose a life-safety threat.*

Table 4: Tentative PFA values and tentative clearance requirements proposed for the seismic classification of acceleration-sensitive non-structural elements in New Zealand

Non-Structural Element Class	Peak Floor Acceleration Capacity*		Installation Clearance Requirements (mm)	
	SLS (No damage)	ULS (Life safety)**	Short Period (T<0.1s)	Medium/Long Period+ (T=1.0s)
A1	0.25g	0.75g	5	50
A2	0.50g	1.00g	10	100
A3	0.75g	1.50g	15	150
A4	1.00g	2.00g	20	200
A5	1.50g	3.00g	30	300

** Refers to median peak floor acceleration for a standardized floor spectrum*
*** Only applicable to those non-structural elements for which failure would pose a life-safety threat.*
+ Fundamental period of non-structural element. Interpolation/extrapolation permitted for other values of period.

For acceleration-sensitive elements, it is recognized that the acceleration demands on an element will depend not only on the floor acceleration response of the main structure but also on the element's inherent damping and period of vibration relative to the building's natural periods of vibration. A number of proposals exist in the literature to provide engineers with a means of estimating such demands using floor acceleration response spectra (e.g. Calvi and Sullivan [10], Vukobratovic and Fajfar [11], Haymes et al. [12]). However, whilst such approaches should be encouraged, it is also recognized that a simplified classification system would ideally be relatively independent of estimates of the building period and floor spectra, particularly given that there will be considerable uncertainty in these quantities. Consequently, as part of the proposed classification system for acceleration-sensitive components, it is intended that the PFA values indicated in Table 4 be linked to the standardized floor response spectrum shown in Figure 1.

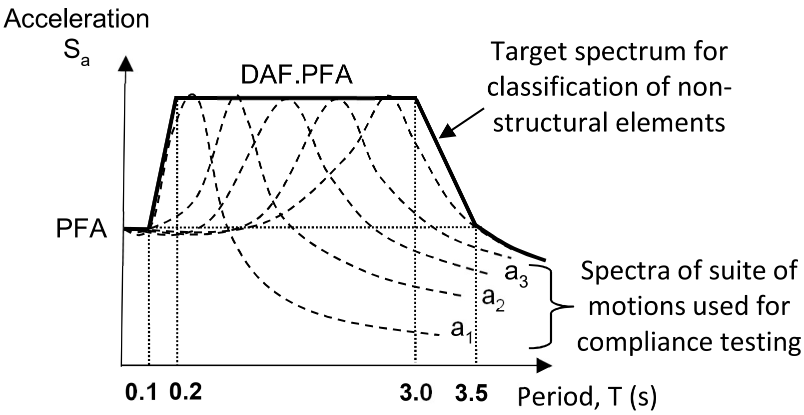

Figure 1: Proposal for a standardized floor response spectrum for the classification of acceleration-sensitive non-structural elements.

The standardized spectrum proposed in Figure 1 shows that the PFA demands (from Table 4) would be specified out to a period of 0.10s (similar to the 0.06s indicated in US standards) but would then rise to an amplified demand at 0.20s and be maintained constant until a period of 3.0s. This very broad plateau of demands does not reflect the shape of floor spectrum demands one should expect in a given building, which instead would be spikey in nature with peaks located at the natural periods of vibration of the building. However, the broad acceleration plateau is proposed so that the floor spectrum in Figure 1 can be applied for a range of buildings typically found in practice, also recognizing that there will be considerable uncertainty as to the exact period of vibration of a building. Potential means of demonstrating compliance with the standardized spectrum will be discussed later in the paper but note here that Figure 1 also indicates spectra for a suite of motions that could be used as part of shake-table testing, rather than running testing with a single motion possessing an unrealistically broad spectral acceleration plateau.

To define the magnitude of the spectral acceleration plateau, Figure 1 shows that the PFA values in Table 4 would be multiplied by a dynamic amplification factor (DAF). The magnitude of the amplification factor depends principally on the damping of the non-structural element and the damping of the supporting structure, as shown in [13]:

$$DAF = \left(0.5\xi_p + \xi_{ns}\right)^{-0.667} \quad (1)$$

where ξ_p is the damping that characterizes the primary structural system (typically taken as 0.05 for RC structures but may be less for steel structures) and ξ_{ns} is the damping that characterizes the non-structural element.

Given the range of non-structural elements that can be encountered in practice, one cannot anticipate a single DAF to be used. As such, as part of the classification process it would be expected that manufacturers or researchers would need to quantify the damping of the non-structural component in order to set the standardized floor response spectrum to be used for component classification.

Envisaged structural engineering process

If the seismic classification of non-structural elements were to proceed as described in the previous section, the engineering design process could be as shown in Figure 2, which extends on the proposal of Filiatrault and Sullivan [14].

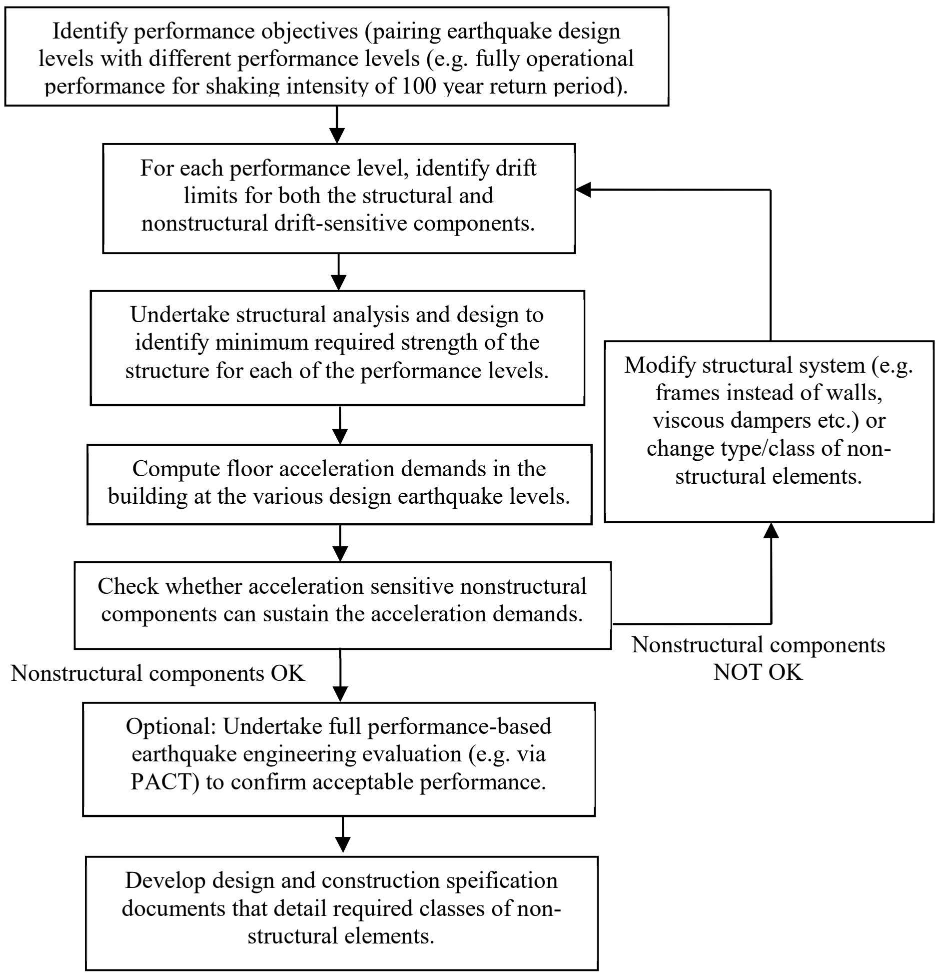

Fig. 2 Performance-based seismic design strategy for nonstructural building components

Figure 2 shows that the engineer would maintain freedom to achieve intended performance objectives a variety of ways. For example, if a stiff-strong RC wall structure were conceived as part of a conceptual design solution then, owing to the low drift demands and high acceleration demands that would result, class D1 and class A3 non-structural components might be appropriate. On the other hand, if an alternative conceptual design solution considered a flexible steel moment-resisting frame system, then floor accelerations would be limited but drifts would be high and so class D3 and class A1 non-structural components might be appropriate. The cost implications of these different design scenarios could then be compared, and other factors considered, to arrive at the ideal concept design solution.

Envisaged process for design, coordination and installation of non-structural elements

The classification framework is intended to ease the design, coordination, tendering and installation process. The framework will provide examples of the types of non-structural element systems (components and restraints) for each classification class. This is intended to help the wider understanding of the compatibility of various non-structural elements, in terms of the required building performance.

The classification tables should be invaluable to structural engineers who are responsible for the seismic design of both the structural and non-structural elements (including those components that are procured through a delegated design-build process) and provide contractors and sub-contractor's clarity on what systems are required for each project.

The structural engineer who is responsible for the design of the structural and non-structural elements of the building would find it easier to work with the design team with the classification framework in place as it will help them understand the components of the building and use the Classification Tables, with inputs from the structural design of the primary structure, to assess the required minimum class for each non-structural element system. Use of the Classification Tables would enable non-structural elements to be included in the design decisions from concept phase when different structural systems are typically considered for the proposed form and layout of the building. The Classification Tables will provide greater understanding of the wider implications of different structural systems on the overall building context and cost.

Non-structural elements comprise around 80% of the cost of buildings, with the primary structure being around 20% of the cost. Consideration of the implications of the structural system on the potential cost of non-structural elements is therefore important. For example, a plasterboard partition wall has a drift limit of around 1 in 300 to onset of damage. A flexible structural system that has an inter-storey drift greater than this limit for the project defined serviceability limit, would require the construction of partitions with seismically split top tracks to enable the top and bottom portions of the partition to move independently. This type of partition system is considerably more expensive than a traditional partition wall that is directly fixed to the floor slab above and below (termed fixed-up fixed-down partitions) and therefore the choice of primary structural system can have considerable implications on the project budget. This is of particular concern if a costly change to a non-structural element system is discovered late in the project.

For non-structural elements that are to be designed, coordinated and installed by the contracting teams (delegated design), the structural engineer would define the relevant drift or acceleration class for each non-structural component. From the contractor's and sub-contractor's perspective this will provide better clarity on the expected non-structural systems for each project. The classification tables should also help provide better consistency in the industry, for both installation and pricing. Current industry practices [15] are resulting in large variations in installation practices for non-structural elements and is making it difficult to achieve a productive and competitive industry as the scope of work for the design, coordination and installation of a non-structural element system can vary markedly between sub-contractors for the same component in a single project. Consequently, the market is being swayed to cheapest price rather than installations that achieve the performance objectives for the building. Using the Classification Tables, the structural engineer of record would be able to coordinate with the contractor and sub-contractors to verify that the coordinated delegated designs for the non-structural elements achieve the defined classifications.

Envisaged process for building inspectors

The classification framework would also lend itself to building inspection. At one end of the scale the classification framework would support simplistic building inspection by knowing what non-structural element classes the structural engineer has defined, and then using the examples of each classification type to inspect each non-structural element system, through to the possibility of the structural engineer on record receiving as-built documentation from which they confirm the coordination, set out and go as far as to assess the period of non-structural elements where the weight of the as-built component is significantly different than originally considered, and from that review the classification class assumed during design, followed by a detailed inspection of the entire installation to confirm the as-built installation achieves the performance requirements for the building.

Summary and Conclusion

Over the past decade there has been an increased recognition in New Zealand that a number of changes to industry approaches should be made to improve the seismic performance of non-structural elements. Gaps have been identified in the understanding of the seismic performance of different types of non-structural elements in existing buildings, and issues have also been noted with the design, procurement and installation processes used for non-structural elements in new buildings [Stanway et al. 2018]. Such observations have motivated the proposal of a seismic classification system for non-structural elements, in which ratings are assigned according to their drift and acceleration capacity. The rating system promises to (i) help engineers to correctly specify and detail non-structural elements for buildings of different importance levels in line with their expected performance in earthquakes, (ii) assist in communicating the performance expectations for all categories of non-structural elements, and (iii) help facilitate inspection and compliance checks for sign-off of non-structural elements. After describing the framework of the proposed rating system, the potential impact of its use has been considered. The discussion suggests that a rating system for non-structural elements could lead to significant improvements in the seismic performance of buildings and thus should be considered further by the industry.

Acknowledgements

This project was partially supported by QuakeCoRE, a New Zealand Tertiary Education Commission-funded Centre. This is QuakeCoRE publication number 0557.

REFERENCES

[1] Stanway, J., Sullivan, T.J., Dhakal, R., (2018) "Towards a New Delivery Approach to Improve the Performance of Non-Structural Elements in New Zealand" 17th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience, Queenstown, New Zealand, November 12-14, 2018.

[2] Filiatrault, A., Sullivan. T.J. (2014) "Performance-based Seismic Design of Nonstructural Building Components: The Next Frontier of Earthquake Engineering", Earthquake Engineering and Engineering Vibration, 13(Supp.1), pp.17-46.

[3] Priestley, M.J.N., Calvi, G.M., Kowalsky, M.J. (2007) "Displacement-based seismic design of Structures" IUSS Press, Pavia, Italy.

[4] Davies, R.D, Retamales, R., Mosqueda, G., and Filiatrault, A. (2011) "Experimental Seismic Evaluation, Model Parameterization, and Effects of Cold-Formed Steel-Framed Gypsum Partition Walls on the Seismic Performance of an Essential Facility Simulation of the Seismic Performance of Nonstructural Systems". Edited by MCEER. Technical Report. Vol. MCEER-11-0. New York: University at Buffalo, State University of New York.

[5] Sassun, K., Sullivan, T.J., Morandi, P., Cardone, D. (2016) "Characterising the in-plane seismic performance of infill masonry" Bulletin of the New Zealand Society for Earthquake Engineering, Vol. 49, No.1, pp.98-115.

[6] Arifin, F., Sullivan, T.J., Dhakal, R., (2020) "Experimental Investigation into the Seismic Fragility of a Commercial Glazing System" W Bulletin of the New Zealand Society for Earthquake Engineering, under review.

[7] Soroushian S (2016). "*Acousitcal tile of lay-in panel suspended ceilings*". Background document FEMA P-58/BD-3.9.31, Applied technology council, Redwood City, CA, 15 pp.

[8] Soroushian S., Zaghi, A.E., Maragakis, M., Echevarria, A., Tian, Y., Filiatrault, A. (2015) "Analytical Seismic Fragility Analyses of Fire Sprinkler Piping Systems with Threaded Joints" Earthquake Spectra, Volume 31, No. 2, pages 1125–1155, May 2015; © 2015, Earthquake Engineering Research Institute

[9] Ghith, A., Ezzeldin, M., Tait, M., El-Dakhakhni, W. (2019) "Shake Table Seismic Performance Assessment of Auxiliary Battery Power Systems Using the FEMA 461 Protocol" Journal of Structural Engineering, Volume 145 Issue 8 – August, https://doi.org/10.1061/(ASCE)ST.1943-541X.0002341

[10] Calvi, P.M. and Sullivan, T.J. (2014) "Estimating floor spectra in multiple degree of freedom systems" Earthquakes and Structures, Vol.6, No.7

[11] Vukobratović, V., and Fajfar, P. (2016) "A method for the direct estimation of floor acceleration spectra for elastic and inelastic MDOF structures" Earthquake Engng Struct. Dyn., 45: 2495– 2511. doi: 10.1002/eqe.2779.

[12] Haymes, K., Sullivan, T.J., Chandramohan, R., (2020) "A practice oriented method for estimating elastic floor response spectra" Bulletin of the New Zealand Society for Earthquake Engineering, *under review*.

[13] Welch, D., Sullivan, T.J. (2017) "Illustrating a new possibility for the estimation of floor spectra in nonlinear multi-degree of freedom systems", Proceedings 16th World Conference on Earthquake Engineering, Santiago, Chile, January 9th to 13th 2017, paper 2632.

[14] Filiatrault, A., Sullivan. T.J. (2014) "Performance-based Seismic Design of Nonstructural Building Components: The Next Frontier of Earthquake Engineering", Earthquake Engineering and Engineering Vibration, Vol.13, Suppl.1, pp.17-46.

[15] Building Innovation Partnership (2020) "Design, Construction and Seismic Performance of Non-Structural Elements" bipnz.org.nz, contact@bipnz.org.nz.

