



Cost-effectiveness of Japanese concrete cladding detailing for improved seismic performance

T.Z. Yeow & K. Kusunoki

Division of Disaster Mitigation Science, Earthquake Research Institute, University of Tokyo, Japan

ABSTRACT

In Japan, it is increasingly common to monolithically construct exterior concrete wall cladding elements to beams and columns, with wall gaps present at plastic hinge locations along beams and reinforcing bars cut at the base of ground floor wing walls to minimize wall damage. This study evaluates the cost-effectiveness of this detailing considering initial construction and damage repair costs. It was found that this detailing resulted in lower drifts and probability of requiring demolition or collapsing, but greater total accelerations. Cost-benefit assessment showed that the monolithic wall construction approach has a time to return-on-investment of 13 years over a bare frame alternative, indicating that there are financial benefits for implementing such systems.

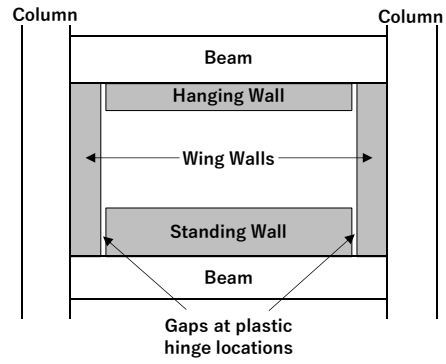
1 INTRODUCTION

Several important buildings in Japan were damaged beyond repair in recent seismic events, such as the Uto City Hall during the 2016 Kumamoto earthquake shown in Figure 1a. As a result, the design seismic demand for buildings of importance was increased in the Japanese building code, resulting in typical reinforced concrete frames being not economical or buildings of importance. One solution adopted in practice is to monolithically construct exterior concrete cladding wall elements to frame elements to increase the frame's overall strength and stiffness with wall gaps provided or wall reinforcing bars cut at ends to limit wall damage as shown in Figure 1b. This paper details a preliminary study to evaluate the cost-effectiveness of utilizing the concrete cladding wall elements to increase the frame's strength and stiffness. Answers to the following are sought:

- 1) Does this detailing reduce the probability of requiring replacement or of building collapse occurring?
- 2) Is this detailing a cost-effective solution compared to bare reinforced concrete frame options?



(a)



(b)

Figure 1: (a) damage to the Uto City Hall, and (b) recent Japanese exterior wall cladding element detailing

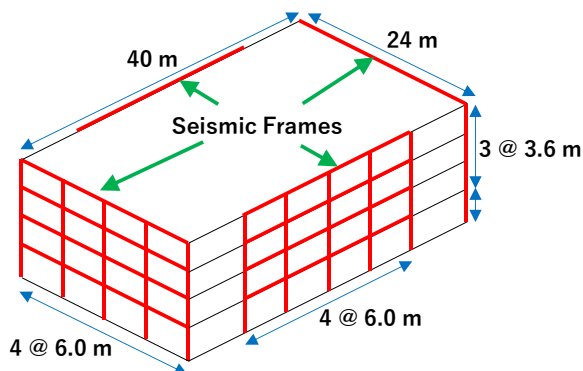
2 METHODOLOGY

2.1 Case study buildings

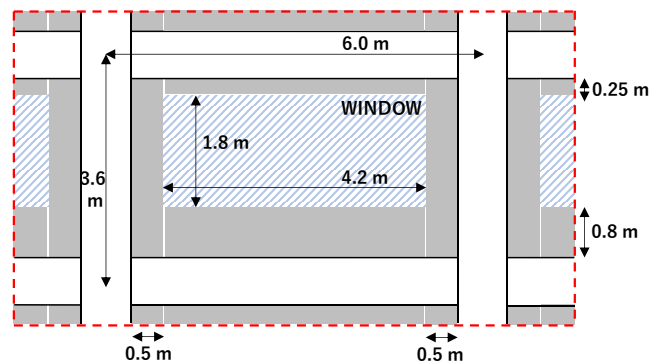
Two buildings were considered in this study, one in which the bare frame alone resists seismic actions, and the other where the concrete cladding elements also contribute. The buildings considered were based on that by Yeow *et al.* (2018), and the general layout is shown in Figure 2a.

The bare frame case was designed to Wellington subsoil class C conditions with importance level 2 following New Zealand Structural Design Actions standards (Standards Australia & Standards New Zealand 2002; Standards New Zealand 2002, 2004) and the Concrete Structures standard (Standards New Zealand 2006). A design ductility of approximately 3.0 and a return period factor of 1.0 was adopted.

For the second building, hanging/standing walls were monolithically attached to the bare frame beams, and wing walls were monolithically attached to the bare frame columns as shown in Figure 2b. All walls had a thickness of 200 mm and used the same concrete material as the frame elements. The reinforcing bars at the base of ground floor wing walls were cut and gaps were provided at ends of hanging and standing walls. The beam and column reinforcing were kept the same as the bare frame case. Due to the presence of the wing walls, the plastic hinge location had shifted closer together, resulting in the storey shear strength of each floor satisfying strength requirements without having to consider the effect of increased stiffness. For consistency, the bare frame case also used concrete wall panels with similar dimensions to that shown in Figure 2b which are connected to the frame using threaded rod connections.



(a)



(b)

Figure 2: Case study building; (a) general layout, and (b) adopted concrete cladding detailing

2.2 Structural modelling approach

Two-dimensional inelastic frame element analysis with corotational effects and 5% Caughey damping (Caughey 1960) was performed. The bilinear Takeda (Takeda *et al.* 1970) and trilinear SINA (Saiidi & Sozen 1979) models were adopted for beams and columns, respectively, with an Emori unloading factor of 0.5. The plastic hinge length was taken as the depth of the bare beam and columns. While this may be counterintuitive for the case with monolithic cladding connections since wall gaps may indicate that a single large crack may form, the walls are thinner compared to the beams and do not contribute any strength, and hence cracks are well distributed as observed in a past experiments (Kono *et al.* 2017; Tani *et al.* 2017). Due to the presence of wall gaps, the hanging and standing walls do not fully contribute to the element's stiffness. Recommendations from Japan Structural Consultants Association (2016) shown in Equation 1 were adopted.

$$\frac{G}{G_0} = \left[\left(\frac{G_1}{G_0} \right)^{2.5} + \left(\frac{G_2}{G_0} \right)^{2.5} \right]^{0.4} \quad (1)$$

where G = combined shear stiffness of the element; G_0 = shear stiffness of the bare frame element; G_1 = shear stiffness of the element considering wall on one side only (e.g. standing wall); and G_2 = shear stiffness of the element considering wall on opposite side (e.g. hanging wall). G_1 and G_2 can be calculated as:

$$\frac{G_{(1 \text{ or } 2)}}{G_0} = \frac{(0.17l' + 0.51)h_w}{D} + (1 - h_w) \quad (2)$$

Where l' = clear span of the element including any wall gaps (m), h_w = depth of the wall of interest (m), and D = depth of the bare frame element (m). Table 1.

Table 1: Member model parameters (bare frame/frame with walls; S – strong direction, W – weak direction)

Member	Depth (mm)	Crack moment (kNm)	Yield moment (kNm)	EI (kNm ²)	Crack to yield ratio	Post yield ratio
Beams – 1 st floor	720	-	911/911	3.18 × 10 ⁵ /3.66 × 10 ⁵	-	0.009/0.008
Beams – 2 nd floor	720	-	784/784	2.76 × 10 ⁵ /3.02 × 10 ⁵	-	0.011/0.010
Beams – 3 rd floor	720	-	628/628	2.16 × 10 ⁵ /2.39 × 10 ⁵	-	0.013/0.011
Beams - roof	720	-	355/355	3.18 × 10 ⁵ /3.66 × 10 ⁵	-	0.013/0.012
Column – outer	800	634/1410	S: 1350/2370 W: 1020/1020	9.80 × 10 ⁵ /1.80 × 10 ⁶	S: 0.28/0.23 W: 0.28/0.16	0.005/0.003
Column – inner	800	782/1040	1540/2190	9.80 × 10 ⁵ /3.20 × 10 ⁶	0.29/0.15	0.005/0.003

2.3 Ground motion records

The ground motion record suite considered in this study were originally selected by Yeow *et al.* (2018) following the Generalized Conditioning Intensity Measure approach (Bradley 2010) considering spectral acceleration at 0.5 s, $Sa(0.5s)$, as the conditioning intensity measure. These were selected to be representative of Wellington subsoil class C seismic conditions. The suite comprises of 9 sets of 20 records, with each set corresponding to different levels of shaking intensity. The seismic hazard for spectral acceleration at a fundamental period of 0.5 s, $Sa(0.5s)$, and the spectral accelerations for the 10% in 50 year shaking set is shown in Figure 3. Note these records are available on the QuakeCoRE wiki (see acknowledgements link).

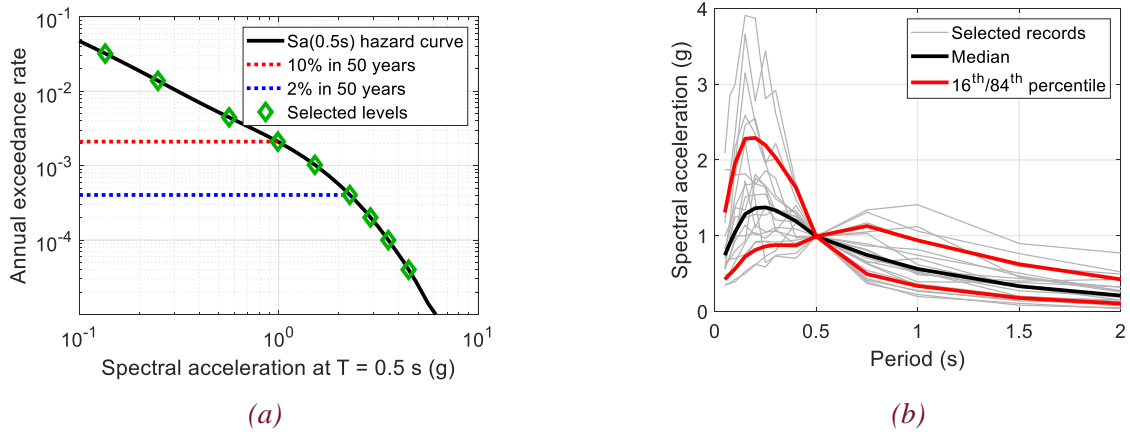


Figure 3: Ground motion information; (a) Sa(0.5s) hazard curve, and (b) 10% in 50 year suite spectra

2.4 Seismic loss estimation

Seismic losses were estimated using the Seismic Loss Assessment Tool, SLAT (Bradley 2011), which solves the Pacific Earthquake Engineering Research Center’s loss assessment framework (Deierlein *et al.* 2003) using the Magnitude-oriented Adaptive Quadrature algorithm (Bradley *et al.* 2009). This is more efficient than alternatives such as the Performance Assessment Calculation Tool, PACT (Naeim & Hagie 2012).

The type, density, fragility, and repair costs of non-structural drift-sensitive components (e.g. interior partitions) and acceleration-sensitive components (e.g. ceilings) adopted in this study are identical to that used by Yeow *et al.* (2018), with the exception of cladding elements. The concrete frame and cladding element costs were estimated using the Rawlinsons construction handbook (Rawlinson & Co. 2015). The damage fragility and repair cost functions for the beam and column was adopted from PACT’s fragility library, while cladding functions for the bare frame case was adopted from Baird (2014). As there were limited information on the onset of damage and repair cost for frame elements with hanging/standing/wing walls, it was assumed that the damage fragility was identical to bare frame elements, but the damage cost was tripled. The breakdown of building cost by component category is shown in Table 2. More details on the components considered are available on the QuakeCoRE wiki (see acknowledgements for link).

Table 2: Breakdown of construction cost of case study buildings

Component category	Bare frame	Frame with walls
Structural (excluding hanging/standing/wing walls)	\$2,160,000	\$2,160,000
Non-structural drift-sensitive	\$940,000	\$970,000
Non-structural acceleration-sensitive	\$5,610,000	\$5,610,000
Total	\$8,710,000	\$8,740,000

3 BUILDING RESPONSE

3.1 Drift and acceleration response in 20% in 50 year shaking event

The peak interstory drift and peak total floor acceleration response during a 20% in 50 year shaking event are shown in Figures 4a and 4b, respectively. Note that this shaking intensity was selected as this was the

greatest shaking level of the nine considered where full-replacement was not required for any of the twenty records. From Figure 4a, the bare frame has greater median peak interstory drifts by 45%-50% as it was more flexible and had lower story strength compared to the frame with walls. In contrast, the frame with walls had greater acceleration response on the upper floors by 4%-26% as shown in Figure 4b. Similar trends were also observed at other intensity shaking levels, and are not elaborated here in greater detail.

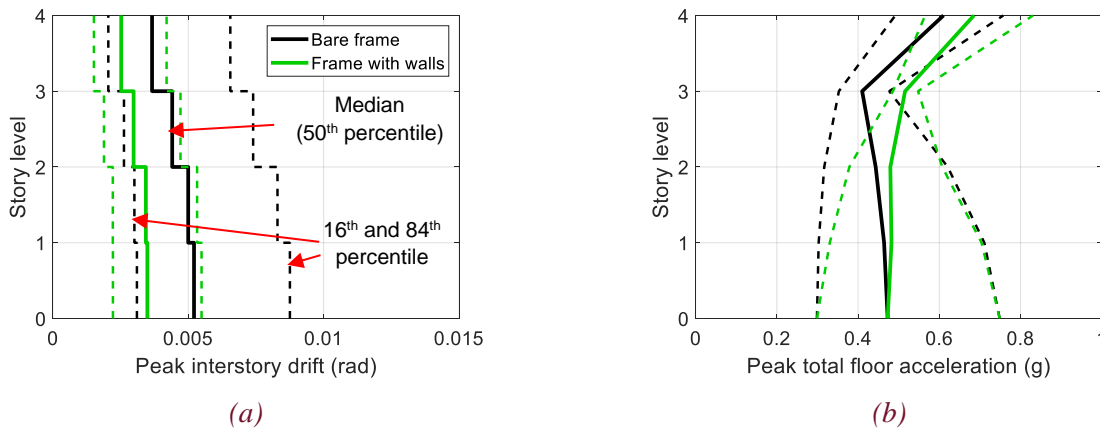


Figure 4: Building response for 20% in 50 years ground motion suite; (a) peak interstory drifts, and (b) peak total floor accelerations

3.2 Demolition and collapse assessment

Drift limits suggested in FEMA356 (ASCE 2000) were adopted to assess if full-replacement was required due to extensive damage (residual and peak interstory drift limits of 0.5% and 2.0%, respectively), and whether it collapsed (peak interstory drift limit of 4.0%). Note that collapse cases also require full-replacement. Based on these limits, the percentage of cases which fit each category was obtained at each shaking intensity and fitted to lognormal distributions. The resulting probabilistic distributions are shown in Figures 5a and 5b for buildings requiring full replacement or collapsing, respectively. Here, the bare frame had a greater probability of requiring demolitions and of collapsing, with a probability of requiring demolition being 25% and 80% for a 10% and 2% in 50 year event, respectively (compared to 14% and 61% for the frame with walls) and a collapse probability of 22% in a 2% in 50 year event (compared to 15% for the frame with walls). The full-replacement probability was further considered in loss assessments, where the full-replacement cost was assumed to be 1.2 times the building value from Table 2.

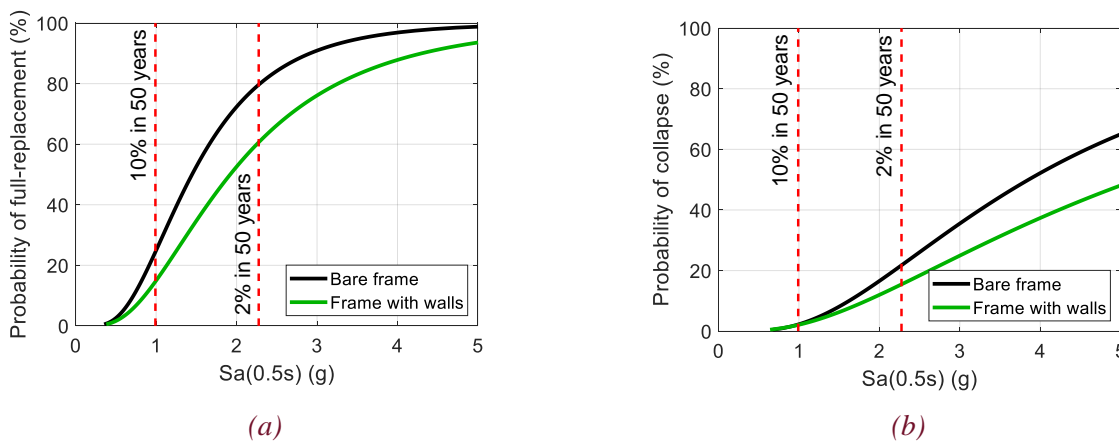


Figure 5: Probability of exceeding global damage state; (a) need for full-replacement and (b) collapse

4 SEISMIC LOSS EVALUATION

4.1 Intensity-based assessment

The breakdown of expected losses at the 20% in 50 year shaking event are shown in Figures 6a and 6b for drift-sensitive (including structural components) and acceleration-sensitive components, respectively. Here, the bare frame had greater drift-related losses compared to the frame with walls, while the opposite is true for acceleration-related losses. Overall, the bare frame incurred \$25,000 more damage at this shaking intensity compared to the frame with walls. Based on the expected loss versus shaking intensity relationship including demolition/collapse losses, shown in Figure 6c, the frame with walls had lower expected losses at all intensity levels observed.

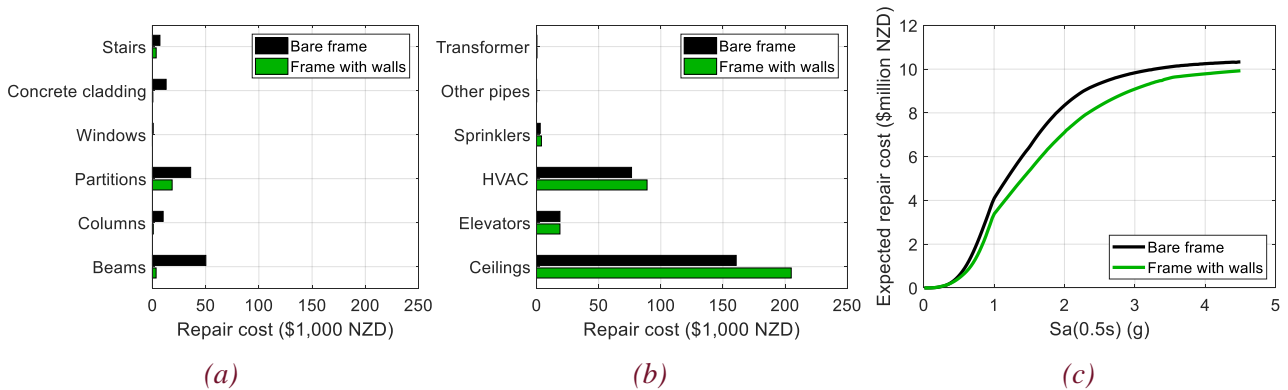


Figure 6: Intensity-based loss assessment; expected losses in (a) drift-sensitive components and (b) acceleration-sensitive components in 20% in 50 year shaking event, and (c) expected damage cost (including demolition/collapse losses) versus shaking intensity,

4.2 Expected annual loss and net-present-cost assessment

Based on the expected loss versus shaking intensity curves shown in Figure 6c, the expected annual loss for the bare frame and the frame with walls were \$23,600 and \$19,900, respectively. Using these values and assuming a discount rate of 6%, the net-present-costs with time considering the difference in initial construction cost and damage losses is shown in Figure 7. Based on this, the time to return on investment for the frame with walls was 13 years, which indicated that the alternate cladding detailing is a cost-effective solution compared to the bare frame option.

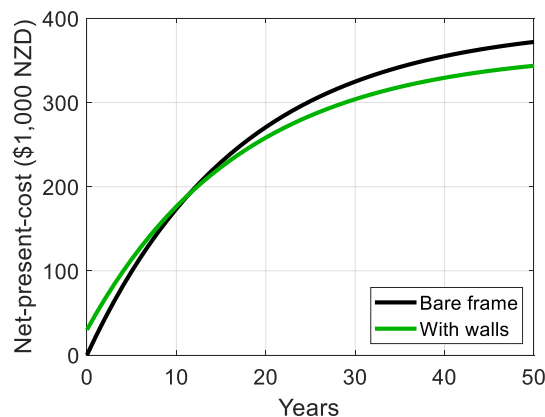


Figure 7: Net-present-value assessment of case study buildings

5 DISCUSSION

5.1 Adopted frame with wall fragility functions

One of the major assumptions made is that the fragility functions were identical for both the bare frame elements and those with walls monolithically attached. The curvature which causes damage should be the same in both cases since the member cross section at the hinge location is identical due to the presence of wall gaps. However, the presence of the walls would make the beam and column elements stiffer and shift the plastic hinge locations closer together, which means that damage could possibly occur at a lower drift. On the other hand, it was assumed that beam and column repair costs would be tripled if walls are attached. As a large component of repair cost comprises of setting up the repair work (e.g. gaining access, propping up elements, etc) and finishing, this is likely to be a conservative assumption. Overall, it is not clear whether the combined effect of the assumptions adopted is conservative overall. Further research into deriving more representative fragility functions and identifying repair strategies for this type of detailing is recommended.

5.2 Acceleration-related losses

While this study shows that overall losses using the frame with wall is lower, it did incur greater acceleration-related losses. In some buildings of importance, such as hospitals, this increased acceleration demand could cause greater damage to contents of importance (e.g. medical equipment, laboratory facilities, etc). Extra considerations and cost may therefore be required to reduce these losses. However, the acceleration-related losses were sizeable for both options in this study, and hence extra considerations may already be required for the bare frame case. If acceleration-related losses are substantially decreased in both cases using other means, then the frame with walls has even greater financial benefit overall.

5.3 Downtime and injuries

The greater accelerations in the frame with walls may not only increase repair costs, but may also cause disruption to functionality (e.g. people may not be able to receive treatment unless medical equipment is replaced) and increase the number of injuries due to content movement or of people falling (Okada *et al.* 2012). However, the bare frame building has a greater chance of needing demolition and collapsing, the latter of which is the greatest cause of deaths in earthquakes (Peek-Asa *et al.* 1998; Petal 2004). The bare frame also had greater structural-related losses, meaning that lengthy repairs may be required before the interior could be repaired. Overall, it is likely that the frame with walls would have lower downtime and injury losses.

6 CONCLUSIONS

In this study, it was found that:

- 1) The frame with walls had a lower probability of requiring demolition or of building collapse occurring compared to the bare frame building.
- 2) The time to return on investment was 13 years if frame with walls is used over the bare frame building, which indicates that this alternative cladding detail is a cost-effective solution.

7 ACKNOWLEDGEMENTS

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Furthermore, information on ground motion records and building components (quantity, fragility, and consequence functions) are available at the following link:

Paper 84 – Cost-effectiveness of Japanese concrete cladding detailing for improved seismic performance

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