- Technical Paper -

INFLUENCE OF EXTERIOR CONCRETE WALL CLADDING DETAILING ON DOWNTIME AND INJURIES

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ABSTRACT

It is increasingly common for exterior concrete wall cladding elements to be monolithically constructed to frame elements to increase the building's strength and stiffness, with special detailing at plastic hinge locations to minimize wall damage. This study evaluates the effectiveness of this detailing on reducing downtime and injuries in a four-story building. It was found that the expected annual downtime and number of injuries decreased by 35-39% and 47-58%, respectively, compared to using a bare frame. This demonstrates strong socioeconomic incentives to implement the monolithic detailing.

Keywords: monolithically connected cladding elements, moment-resisting frame, downtime, injuries

1. INTRODUCTION

Recently it is becoming common in Japan to monolithically construct concrete hanging, standing, and wing walls to beams and columns. This detailing is a simple solution to increase the strength and stiffness of buildings of greater importance. To limit damage to the walls, wall gaps are present at plastic hinge locations along the beams, and wing wall flexural reinforcing are sometimes cut at its base on the ground floor. This was shown to work reasonably well in past studies [1, 2]. An example of this detailing is shown in Fig. 1.

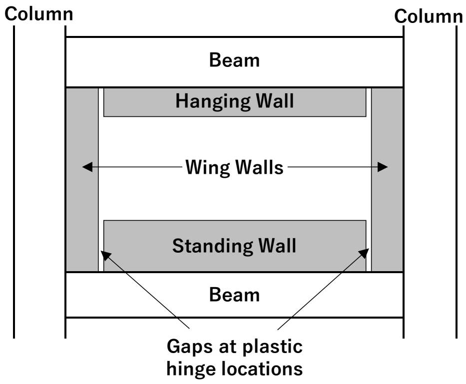

Fig.1 Exterior wall cladding detailing

A previous study by the authors of this paper (see acknowledgements) investigated the cost-effectiveness of a frame with the hanging/standing/wing walls monolithically constructed to a reinforced concrete frame against that of a bare frame. The study considered two 4-story buildings; one for each building solution. It was found that the frame with walls was a cost-effective solution, with the time to return-on-investment being just 13 years. However, other socioeconomic impacts arising from occupancy disruption, commonly referred to as "downtime", and injuries were not examined.

This study extends the previous case study to quantify the effect of monolithically constructing wall cladding elements to beams and columns on downtime and injuries. Answers to the following are sought:

(1) How effective is the alternative detailing in reducing downtime?
(2) How effective is the alternative detailing in reducing injuries?

2. PREVIOUS STUDY DESCRIPTION

The general layout of the two buildings considered in the previous study are shown in Fig. 2a. Identical exterior seismic frames are used along each side of the building. The buildings considered were located in Wellington, New Zealand, on subsoil class C seismic conditions. The bare frame was designed to meet requirements from the New Zealand design action standards [3-5] and concrete structures standard [6]. In the case of the monolithically connected cladding (hereby termed "frame with walls"), the same exact bare frame was reused with 200 mm thick hanging, standing, and wing walls monolithically connected as shown in Fig. 2b. Note that details on wall reinforcing was not provided as these do not contribute to the frame element strengths within the plastic hinge regions.

Two-dimensional inelastic dynamic analysis using one-component Giberson elements were performed to obtain the buildings' response. Corotational effects and 5% Caughey [7] damping were included. The hysteretic behavior of the beams and columns were modelled using bilinear Takeda [8] and trilinear SINA [9] models, respectively. The increase in beam stiffness due to the

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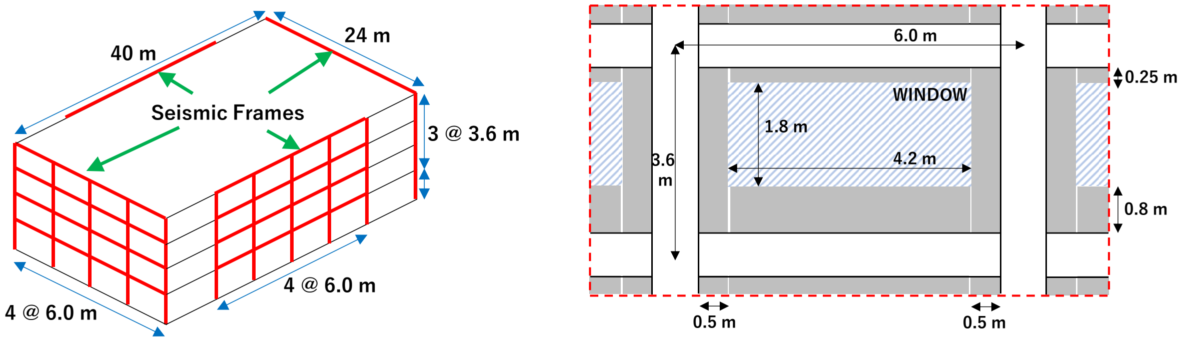
presence of hanging/standing walls for the monolithic wall connection case was considered following recommendations from the Japan Structural Consultants Association [10]. The member stiffness and strength properties used in the modelling are shown in Table 1, where (i) left-hand values represent the bare frame properties while the right-hand values represent the building with hanging/standing/wing walls, and (ii) *S* and *W* represent the strong and weak bending directions for outer columns which only have wing walls on one side. Damage to beam-column joints was ignored for both cases as the building had been detailed for plastic hinges to only occur at the beam ends and column base following capacity design methodology.

A suite of ground motion records representative of Wellington subsoil class C conditions, which was previously selected by Yeow et al. [11], was used. This suite consists of 9 sets of 20 records, with each set representative of a given shaking intensity level. The seismic hazard for spectral acceleration corresponding to 0.5 s, *Sa*(0.5s), which was selected as the intensity measure (*IM*), is shown in Fig. 3a, while the 10% in 50 year ground motions used is shown in Fig. 3b.

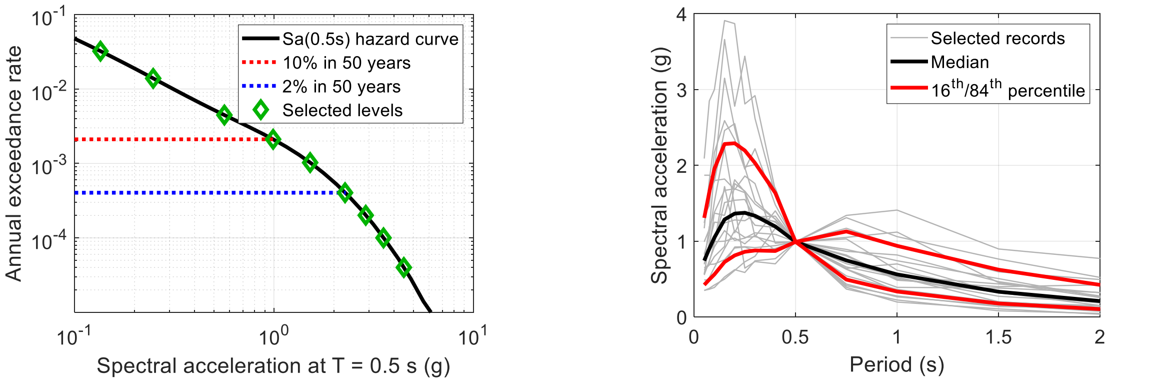
Based on the analyses performed, the distribution of peak interstory drift for the set of records corresponding to a 20% in 50 year event was obtained as shown in Fig. 4. The median peak interstory drift for the bare frame was between 45-50% greater than that for the frame with walls. Trends at other shaking intensity levels were observed to be similar.

In addition to interstory drifts, peak total floor accelerations were also investigated. As this will not used in this study, the results are not presented here. Both the drift and acceleration results were used to estimate seismic losses in terms of direct-repair costs, where it was found that the frame with walls was a more cost-effective solution within a building's design service life of 50 years. This current study will extend on the work from the previous study by considering other socioeconomic factors (i.e. downtime and injury).



(a) (b)

Fig. 2 Case study building details; (a) building layout, and (b) cladding layout



(a) (b)

Fig. 3 Ground motion details; (a) *Sa*(0.5s) seismic hazard curve, and (b) 10% in 50 year suite spectra

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 (10^5 kNm^2)	Crack to yield stiffness ratio	Post yield stiffness ratio
Beams – 1st floor	720	-	911/911	3.18/3.66	-	0.009/0.008
Beams – 2nd floor	720	-	784/784	2.76/3.02	-	0.011/0.010
Beams – 3rd floor	720	-	628/628	2.16/2.39	-	0.013/0.011
Beams – roof	720	-	355/355	3.18/3.66	-	0.013/0.012
Column - inner	800	782/1040	1540/2190	9.80/32.0	0.29/0.15	0.005/0.003
Column – outer (*S*)	800	634/1410	1350/2370	9.80/18.0	0.28/0.23	0.005/0.003
Column – outer (*W*)	800	400/400	1020/1020	9.80/18.0	0.28/0.16	0.005/0.003

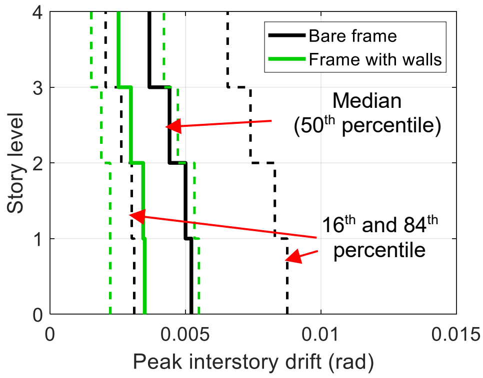


Fig. 4 Peak interstory drift comparisons for 20% in 50 year event

3. METHODOLOGY

3.1 Overall methodology

The HAZUS [12] methodology was adopted to estimate downtime and injuries. While other approaches were available, this approach was simpler to apply, and may not necessarily be less accurate given the highly uncertain nature of estimating downtime and injury. As this study's main objective is to compare the relative performance of the two buildings, it was deemed that the HAZUS approach was sufficient for this need. The methodology consists of three parts; (i) global damage state assessment, (ii) downtime assessment, and (iii) injury assessment.

3.2 Global damage assessment

Global damage assessment was used to categorize the entire building's damage severity which is required for downtime and injury assessments. Five classes were defined; (i) no damage, (ii) light, (iii) moderate, (iv) extensive, and (v) complete. This assessment was done by firstly recording the peak interstory drift across the entire building for each individual analysis performed. A lognormal median, x_m, and dispersion, β, was then calculated for each hazard level considered as follows:

$$x_m = e^{\sum \ln(x)/n} \quad (1)$$

$$\beta = \sqrt{\frac{\sum(\ln(x)-\ln(x_m))^2}{n-1}} \quad (2)$$

where,

x : peak interstory drift for a given case

n : number of cases considered

Global damage fragility functions are available from HAZUS [12] for various types of mid-rise concrete buildings designed for high seismic zones, the definition of which is provided in the 1994 UBC lateral force design requirements [13]. The bare frame was classified as a "Frame Building". While the frame with walls would behave similarly to a frame building, it was categorized as a "Shear Wall Building" for conservatism. The resulting drift limits are listed in Table 2. Monte Carlo simulations were performed using both the lognormal distribution of peak interstory drifts and the global damage fragility functions to estimate the probability of incurring a given damage state.

Table 2 Global damage state fragility function [12]

Damage state	Frame		Shear Wall	
	Median	Dispersion	Median	Dispersion
Light	0.0033	0.68	0.0027	0.74
Moderate	0.0067	0.67	0.0067	0.77
Extensive	0.0200	0.68	0.0200	0.68
Complete	0.0533	0.81	0.0533	0.77

3.3 Downtime assessment

The duration of occupancy disruption for a given building is provided by HAZUS [12]. These values are based on the damage state of the building and the building's usage type. While dozens of different usage types were listed in HAZUS [12], the main usage types which are more relevant to the case study buildings were divided into the following four main categories based on the downtime duration:

(i) Category I: banks and financial institutions, emergency response
(ii) Category II: general government buildings, schools and libraries
(iii) Category III: hospitals
(iv) Category IV: multifamily dwelling, college and universities

Downtime values provided by HAZUS [12] are shown in Table 3.

Table 3 Downtime values (in days) [12]

Usage category	Damage state			
	Slight	Moderate	Extensive	Complete
I	10	90	270	360
II	10	90	360	480
III	20	135	540	720
IV	10	120	480	960

The expected downtime for usage category j, $Time_j$, was calculated as shown in Equation (3).

$$Time_j(IM) = \sum_{i=slight}^{complete} P(DS_i|IM).T_j(DS_i) \quad (3)$$

where,

i : global building damage level

$P(DS_i|IM)$: probability of incurring damage level i at given IM value

$T_j(DS_i)$: downtime for damage level i and usage category j from Table 3

It should be noted that HAZUS [12] provided correction factors which decreases the length of downtime to account for the fact that the building's occupants may be able to relocate and work from a different location following an earthquake. However, as the focus of this study is on the downtime of the building itself, the correction factors were not applied.

3.4 Injury assessment

HAZUS [12] defined four injury severity levels; Level 1 (injuries only requiring basic medical aid), Level 2 (more serious but non-life-threatening injuries), Level 3 (life-threatening injuries) and Level 4 (fatal injuries). Injury rates for each injury severity level are dependent on the building's global damage level and structural form. The injury rates for all types of concrete buildings are shown in Table 4, where "collapse" was assumed to occur in 10% of complete damage cases.

Table 4 Injury rates [12]

Damage State	Injury severity level			
	1	2	3	4
Light	0.05 %	-	-	-
Moderate	0.25 %	0.03 %	-	-
Extensive	1.00 %	0.10 %	0.001 %	0.001 %
Complete (no collapse)	5.00 %	1.00 %	0.01 %	0.01 %
Complete (collapse)	40.0 %	20.0 %	5.00 %	10.0 %

The expected number of injuries at the k^{th} injury severity level, Inj_k, can be calculated as follows:

$$Inj_k(IM) = \sum_{i=slight}^{complete} P(DS_i|IM).I_k(DS_i) \quad (4)$$

where,

k : injury severity level

$I_k(DS_i)$: number of injuries of k severity for damage level i from Table 3

4. GLOBAL DAMAGE STATE COMPARISON

The lognormal distribution of peak interstory drift from the previous study across the entire building versus shaking intensity level were calculated using Eqs. 1 and 2, and are shown in Table 5. Here, the frame with walls consistently had lower drifts compared to the bare frame case.

Table 5 Lognormal distribution of drifts (in rad)

Shaking level	Sa(0.5s) (g)	Bare frame		Frame with walls	
		x_m	β	x_m	β
1	0.135	0.0014	0.35	0.0010	0.13
2	0.245	0.0027	0.47	0.0017	0.12
3	0.564	0.0063	0.51	0.0044	0.43
4	0.991	0.0139	0.54	0.0096	0.51
5	1.52	0.0199	0.63	0.0150	0.59
6	2.28	0.0305	0.58	0.0235	0.57
7	2.89	0.0372	0.62	0.0291	0.57
8	3.55	0.0409	0.52	0.0317	0.53

Using the fragility functions from Table 1 and Monte Carlo simulation (using 500,000 trials per shaking level and damage state), the probability of incurring any damage state was calculated and is shown in Fig. 5. Here, the bare frame building had a greater probability of incurring any damage state compared to the frame with walls. Note that results greater than $Sa(0.5s)$ = 2.0 g were not shown as the difference in probabilities is less obvious, though the bare frame still had greater probabilities at those shaking intensity levels.

The breakdown of probability by damage state for $Sa(0.5s)$ = 0.991 g is shown in Fig. 6. Although the frame with walls have a greater probability of incurring slight damage, the bare frame building had greater probabilities of incurring more severe damage states. This trend was also observed at other shaking levels. Together with Fig. 5, these results indicate that the bare frame building is more likely to incur damage, and that the damage is also likely to be more severe.

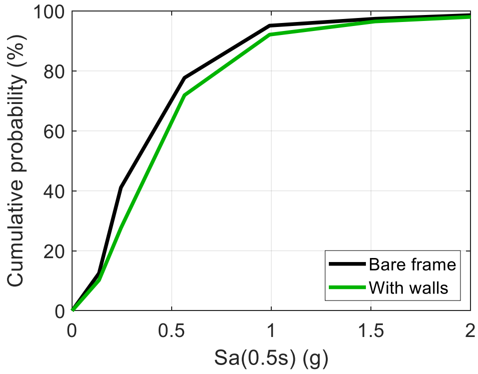


Fig. 5 Cumulative probability of incurring any level of damage

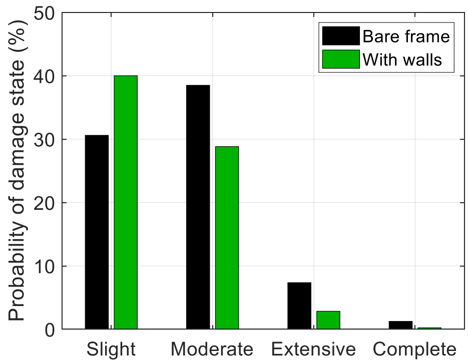


Fig. 6 Disaggregation of cumulative probability at Sa(0.5s) = 0.991g by building damage state

5. DOWNTIME COMPARISON

The expected downtime for both buildings were calculated using Eq. 3 for each usage category type. The downtime duration for the frame with walls was then subtracted from the duration for the bare frame case, and the resulting difference is shown in Fig. 7. As the difference was always positive, the downtime duration for the bare frame case was always larger.

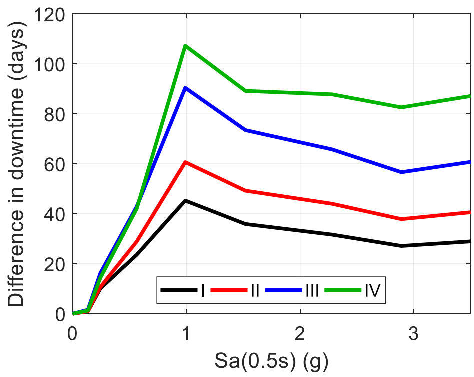


Fig. 7 Difference in downtime estimate between bare frame and frame with walls case

The peak difference in downtime occurred at $Sa(0.5s)$ = 0.991 g for all usage categories considered, and ranged from 45 to 107 days. This indicated that multifamily dwellings (category IV) constructed with bare frames may not be occupiable for up to 3 months more than frame with walls, and hence temporary shelters would be in greater demand for a longer duration. Likewise, hospitals and schools constructed with bare frames may also not be usable for several months more compared to frame with walls and would thus cause significant disruption to the health and education sector.

While the difference in downtime decreased after Sa(0.5s) = 0.991 g, the actual value of downtime for each building never decreased. The decrease in the difference in downtime values at larger shaking intensity is expected as both buildings would eventually incur complete damage once Sa(0.5s) becomes large enough, at which time the downtime values would be similar.

6. INJURY COMPARISON

The number of injuries per 1,000 people, calculated using Eq. 4, are shown in Fig. 8. Here, the bare frame (solid lines) incurred more injuries across all injury severity levels compared to the frame with walls (dashed lines).

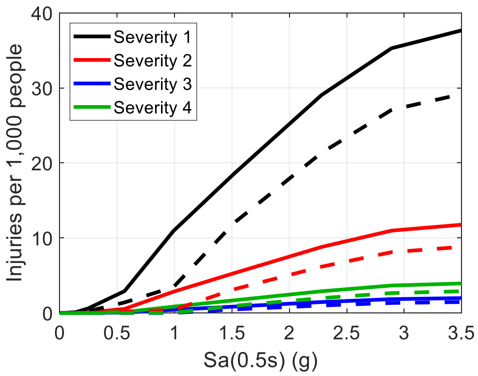


Fig. 8 Estimated injuries per 1,000 people (solid line – bare frame, dashed line – frame with walls)

7. EXPECTED ANNUAL VALUE COMPARISON

The downtime and injury versus shaking intensity results can be combined with the seismic hazard curve from Fig. 3a to obtain expected annual values from Equation (5) (Bradley, et al. [14]):

$$E_L = E_{L|IM}(im).\left|\frac{d\lambda_{IM}(IM)}{dIM}\right|.dIM \tag{5}$$

where,

E_L : expected annual value of loss L
IM : shaking intensity measure
$E_{L|IM}$: expected value of loss L at given IM
λ_{IM} : seismic hazard curve for IM

The expected annual loss for downtime and injuries are shown in Table 6. The frame with walls had a 35-39% reduction in expected annual downtime, and a 47-58% reduction in expected annual injuries. While the size of annual losses was relatively small, particularly for injuries, it does provide further proof that the frame with walls is likely to have better performance considering that the cost-assessment in the previous study was already in favor of the frame with walls within its design service life of 50 years.

Table 6 Expected annual loss in terms of downtime and injuries

Loss type	Category	Expected annual loss	
		Bare frame	With walls
Down-time	I	1.2 days	0.7 days
	II	1.4 days	0.9 days
	III	2.1 days	1.3 days
	IV	2.0 days	1.2 days
Injuries	1	0.080	0.043
	2	0.020	0.009
	3	0.003	0.001
	4	0.006	0.002

8. FURTHER DISCUSSIONS

A key aspect of the approach adopted is that downtime and injuries were evaluated solely based on peak interstory drift. In reality, accelerations and velocities could also be a key factor. As the frame with walls is stiffer and stronger than the bare frame, it would have greater acceleration response and could incur more fall-related injuries [15-17]. However, while not shown here, the accelerations observed in the previous study are sizeable for both the bare frame and the frame with walls. As such, the frame with walls is not expected to have a significantly larger number of fall-related injuries.

The increase in accelerations could also cause more furniture to move in the building, which is one of the major causes of injuries during the 2010-2011 Canterbury earthquake sequence in New Zealand [18]. However, the injury to occupants does not necessarily arise from the onset of furniture movement, but rather the extent of it. Yeow, et al. [19] noted that a building with a longer fundamental mode period could have greater furniture movement, and hence the greater accelerations for the frame with wall does not necessarily imply that more injuries would occur due to furniture movement.

Finally, the increased accelerations could also cause greater damage to building components sensitive to accelerations, such as ceilings. This would potentially increase the building's downtime as well, and is particularly important in hospitals and research facilities. Therefore, the frame with walls might require further consideration to reduce damage to acceleration-sensitive components. However, as mentioned earlier, the size of acceleration response is quite large in both the bare frame building and the frame with walls, and it is likely that the bare frame building would also need some considerations. Therefore, this is unlikely to affect the downtime estimates if special considerations were made to reduce acceleration-related damage in both buildings.

9. CONCLUSIONS

The key conclusion from this study are as follows:

(1) The frame with walls had better performance

compared to the bare frame building in terms of downtime, as it had up to 107 days reduction depending on the shaking intensity, and a 35-39% reduction in expected annual downtime.

(2) The frame with walls also had better performance in terms of injuries compared to the bare frame, with up to a 47-58% decrease in expected annual injury numbers.

ACKNOWLEDGEMENTS

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