Investigating the effect of stiffness on the seismic performance of RC structures

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ABSTRACT

This study investigates the correlation between stiffness and the seismic performance of RC structures. Structural performance was compared for buildings affected by four different earthquakes, Tokachi-Oki (1968), Chile (1985), New Zealand (2011) and Taiwan (2016). The priority index, a proxy for stiffness, was used as a means of quantifying structural performance. The priority index is calculated as the sum of wall area in one orthogonal direction and half of the column area, divided by the total floor area above ground. The results show that buildings with a small priority index are more susceptible to severe damage. Structures surveyed in Christchurch had the smallest priority index on average (0.14 %) and had the highest frequency of severe damage (54%). Buildings in Chile and Japan had an average wall index of 0.35%, four times greater than structures surveyed in Taiwan and Christchurch. Buildings with a wall index greater than 0.20% were 15x less likely to have severe damage. The results indicate that stiffer structures perform better.

1 INTRODUCTION

Earthquake reconnaissance has consistently observed that stiffer structures experience less damage (Riddell et al. 1987; Sozen 1989; Fintel 1995; Ghosh 1995; Sezen et al. 2003; Sarrafzadeh et al. 2017). Little effort has been made to quantify this. In this paper, the performance of structures in different countries is quantified by correlating damage to stiffness. Four earthquakes were investigated, Tokachi-Oki (1968), Chile (1985), New Zealand (2011) and Taiwan (2016). The intensity of ground motion produced by each earthquake was compared by plotting the response spectra and measuring the Arias Intensity (I_A) and significant duration ($Ds_{5\text{-}75}$). No ground motion data was available for the 1968 Tokachi-oki Earthquake. Priority index was used as a surrogate for stiffness. Damage was then plotted against priority index to understand how changes in the column and wall cross sections affect the performance of the structure. Each reconnaissance report defined 'moderate' and 'light' damage differently. To ensure consistency among building data, damage was defined as 'severe' or 'other'. Severe damage was characterised as large shear cracks or local structural failure.

2 EARTHQUAKE RECONNAISANCE AND GROUND MOTION DATA

Sections 2.1 to 2.4 summarise the reconnaissance observations from each earthquake. Section 2.5 provides a comparison of the ground motions by comparing the response spectra, Arias Intensity (I_A) and significant duration (Ds_{5-75}). The similar intensity of shaking for these earthquakes provided an opportunity to directly compare the performance of structures across the regions.

2.1 Tokachi-oki Earthquake 1968

The M_w 8.3 earthquake occurred on the 16th of May, 1968 and resulted in 48 deaths. The peak recorded ground acceleration (PGA) was 0.24g. Ground motion records were unavailable so it was not possible to characterise the intensity of ground motions produced. Shiga et al. (1977) observed that most of the severely damaged structures had fewer structural walls. A total of 245 buildings ranging from 1 to 5 storeys were surveyed. No buildings with a wall index of 0.3% or greater experienced severe damage.

2.2 Chile 1985 Earthquake

The magnitude 8.0 (M_w) Chile earthquake produced ground motion with a PGA of 0.67 g in Llolleo, and 0.36 g in Viña del Mar. The peak ground velocity (PGV) was computed by integrating the ground motion acceleration record. The PGV in Viña del Mar was 0.41 m/s. Damage reports following the earthquake indicated that minimal damage was observed in RC wall structures (Riddell et al. 1987; Wood et al. 1987; Sozen 1989; Wood 1991). Of the 178 buildings assessed in Viña del Mar, only 6 suffered moderate to severe damage, five of which were repaired (Wood et al. 1987). The Canal Beagle apartments had severe damage attributed to topographical amplifications (Celebi 1987). The 5% damped, mean response spectra of the ground motion records from Viña del Mar, Llolleo and Melipilla is plotted in Figure 1.

2.3 Christchurch 2011 Earthquake

The magnitude 6.2 (M_w) Christchurch earthquake had a PGA in the CBD of 0.72g and a PGV of 0.84 m/s. Two mid-rise RC office buildings and a parking garage collapsed (Kam et al. 2011). The financial loss following the earthquake was estimated to be $40 billion dollars, 20% of New Zealand's GDP (Gonzalez et al. 2021). There were 254 RC buildings in the CBD over two storeys. From the data available on 223 of these structures, 138 (62%) were demolished after the earthquake (Elwood et al. 2015). Of the nine steel buildings in the CBD, three were demolished and two required extensive repairs to the lateral load resisting system (Clifton et al. 2011; Elwood et al. 2015). Figure 1 shows the 5% damped mean spectra of the ground motion records in the Christchurch CBD.

2.4 Taiwan 2016 Earthquake

A magnitude 6.4 (M_w) earthquake struck southern Taiwan on 6th February 2016. The PGA recorded was 0.46 g and the PGV was 0.69 m/s. An NZSEE reconnaissance team assessed 121 mid-rise RC buildings following the earthquake. 28 buildings (23%) were had severe damage (Pujol et al. 2020). One building collapsed and three buildings partially collapsed due to soft story failure in the first floor (Henry et al. 2017). Ground motion records were obtained from three stations (CHY089, CHY062, CHY063) located within Tainan City and the 5% damped mean response spectrum was plotted (Figure 1).

2.5 Ground motion comparisons

PGA, PGV, Arias Intensity (I_A) and significant duration (Ds_{5-75}) were computed for the ground motion records from each earthquake (Table 1). Arias Intensity represents the energy content of a ground motion and is calculated as the cumulative integral of acceleration squared. Ds_{5-75} is the significant duration of shaking, characterised as the time over which 5 to 75% of the Arias Intensity (I_A) is accumulated. Chile (1985), Christchurch (2011), and Taiwan (2016) exhibit similar levels of shaking based on the peak ground acceleration and peak ground velocity. The long duration of the Chile 1985 earthquake suggests that the intensity of shaking was greater than that of Taiwan or Christchurch.

Table 1: Comparison of mean intensity measures for the three earthquakes.

	PGA (g)	PGV (m/s)	I_A (m/s)	Ds_{5-75} (sec)
Christchurch	0.42	0.59	3.8E4	4.0
Taiwan	0.37	0.48	1.7E4	2.4
Chile	0.50	0.36	1.1E5	24.3
Tokachi-Oki	0.24	-	-	-

Because of the stiffness of buildings in Chile, along with the majority of structures in Christchurch, Taiwan, and Japan having fewer than 10 storeys, it is expected that almost all of the surveyed buildings had a period shorter than 1.0 second. The mean displacement spectra for the three earthquakes indicate a very similar intensity of shaking for buildings with a period of 1.0 second or less.

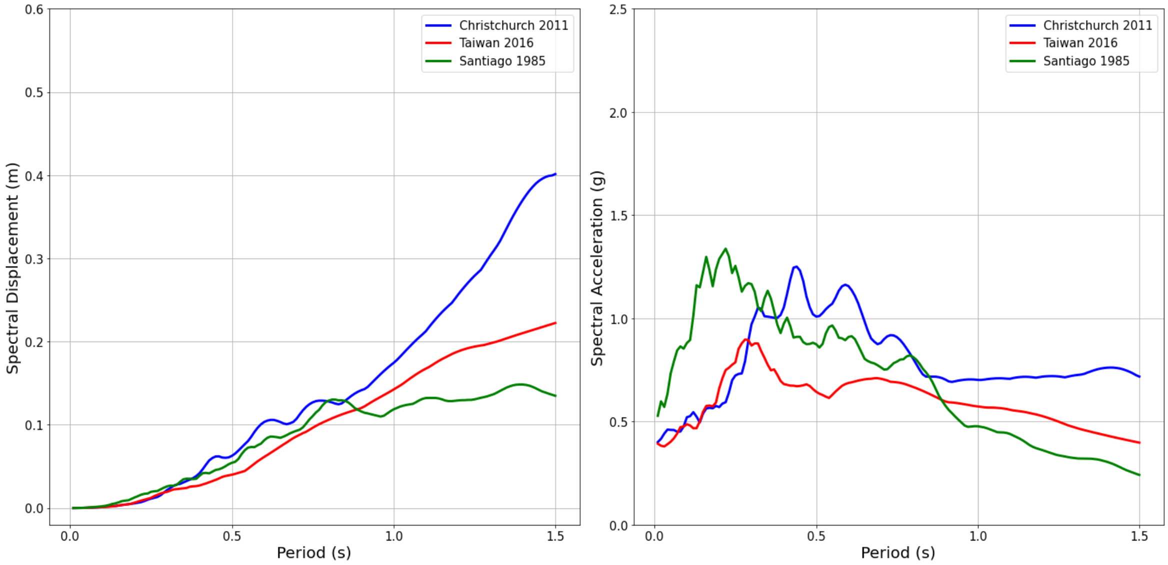


Figure 1: Mean response spectra of ground motions recorded from the Christchurch 2011, Chile 1985, and 2016 Taiwan earthquakes.

3 PRIORITY INDEX

The objective of this research is to quantitatively compare the performance of structures and understand how stiffness influences performance. Because of the limited data available, the Hassan Index was used as a surrogate measure for stiffness. The Hassan Index, also knowing as the priority index (PI), was initially developed as a screening method to identify seismically vulnerable structures and was based on the "SST Format" proposed by (Shiga 1977). Hassan and Sozen (1997) proposed the Hassan Index by evaluating structures of seven storeys or fewer. This study has included buildings up to 23 storeys tall in Chile and New Zealand to provide a larger sample of structures. The index is calculated as the sum of wall index (WI) and column index (CI) as seen in Equations 1-3 below. $\sum A_f$ represents the total floor area of the structure above ground. A_{wt} and A_{mw} are the 1st floor concrete wall area and masonry wall area in the most critical direction, and A_c is the area of columns in the 1st storey.

$$PI = WI + CI \quad (1)$$

$$WI = \frac{A_{wt}}{\sum A_f} + \frac{1}{10}\frac{A_{mw}}{\sum A_f} \quad (2)$$

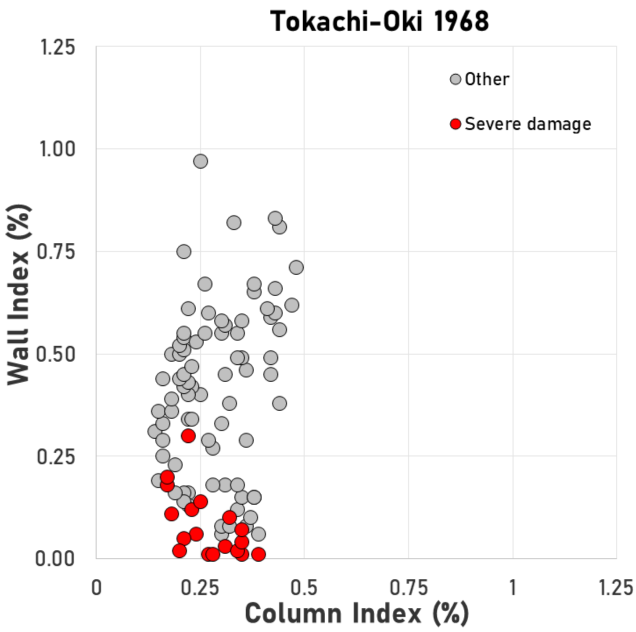
$$CI = \frac{1}{2}\frac{A_c}{\sum A_f} \tag{3}$$

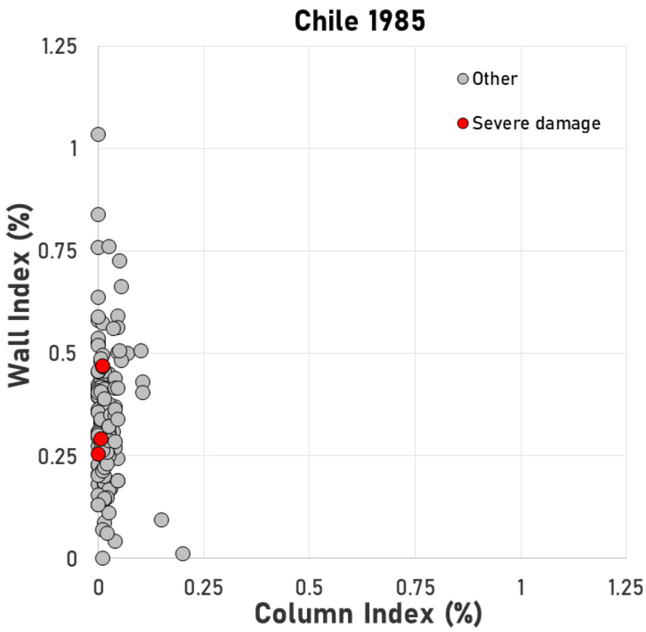
As indicated by Gülkan and Sozen (1999) and Pujol et al. (2020) there is uncertainty associated with using such a simple metric to estimate structural performance. Recorded ground motions in a city can exhibit large variations in intensity. Even for buildings located in close proximity, subject to similar levels of shaking, performance can further differ due to building quality and details such as concrete cover, the location of lap-splices or the layout of the lateral load resisting system. The priority index also does not account for the quantity of reinforcement in columns and walls, or the spacing of ties. And yet, the index has been shown by past studies to provide an effective and simple method of identifying vulnerable and resilient structures.

4 RESULTS

Wall and column index data was available from reports and reconnaissance following Tokachi-Oki (1968), Chile (1985), and Taiwan (2016). For buildings in Christchurch, damage reports and structural drawings were available for dozens of buildings. Photos from damage reports were used to identify severely damaged structures. Wall and column index data was calculated and plotted for 24 buildings following the Christchurch 2011 Earthquake. Plots were developed for each earthquake with column index on the x-axis and wall index on the y-axis (Figure 2). Damage was categorized as 'Severe' or 'Other'.

Surveys of buildings after large earthquake events often focus on buildings that have experienced extensive damage (Pujol et al. 2020). For the 1968 Tokachi-Oki Earthquake, 254 buildings between 1 and 5 storeys were surveyed to find trends between damage and the quantity of walls and columns in each structure (Shiga et al. 1977). The researchers focused on finding trends in the damage of these structures (looking at both damaged and undamaged buildings) so the data may not be representative of the building inventory. The same is true for the 103 buildings surveyed in Taiwan (2016). All of the mid-rise structures in Viña del Mar (ranging from 5 – 23 storeys) were surveyed following the 1985 Chile earthquake (Riddell et al. 1987). Damage reports and building drawings were available for 24 buildings in Christchurch following the 2011 earthquake. 54% had severe damage while Kam et al. (2011) stated that approximately 24% of buildings in the CBD had severe damage after the earthquake, suggesting that the buildings investigated may not be representative of the Christchurch building inventory.





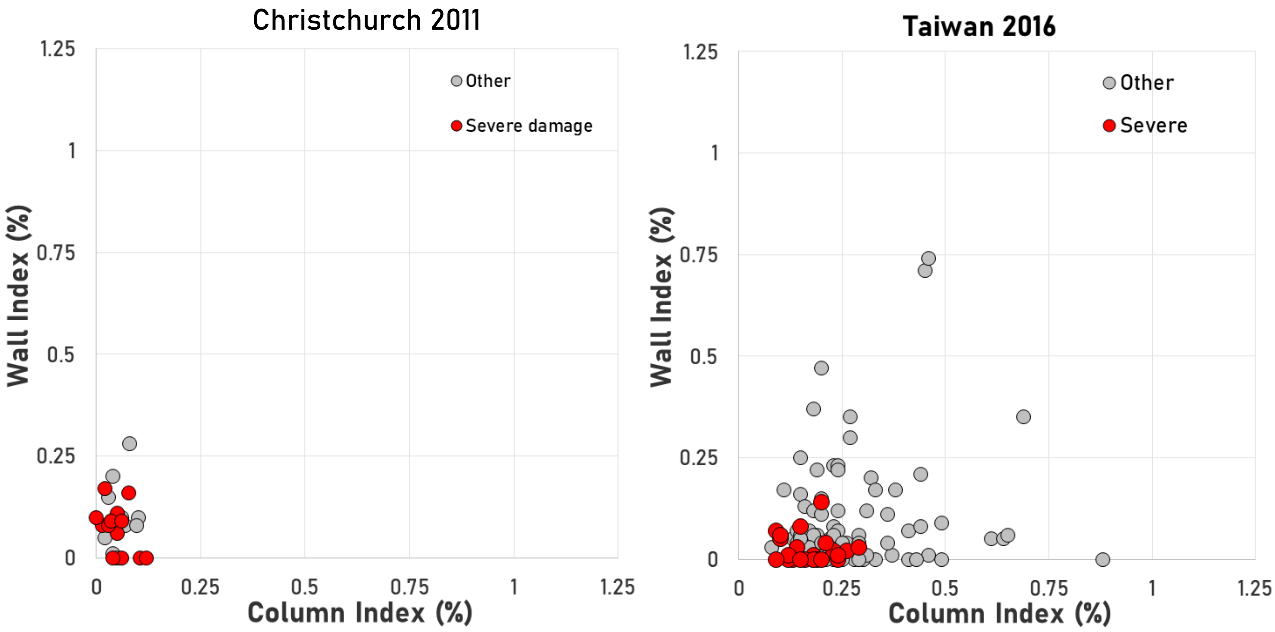


Figure 2: Scatter plots of wall index (WI) vs column index (CI) for buildings in a) Japan, b) Chile, c) New Zealand, and d) Taiwan, with damage severity indicated by colour.

Table 2 provides a summary of the mean structural indices for buildings and the damage they experienced under each earthquake. 2% of buildings in Viña del Mar suffered severe damage, while over 50% of buildings in Christchurch experienced severe damage under a similar intensity earthquake. 17% of buildings surveyed in Japan and 20% of structures assessed in Taiwan had severe damage.

Table 2: % of buildings experiencing severe damage during each earthquake as well as mean wall, column, and priority index values.

	Severe (%)	WI (%)	CI (%)	PI (%)
New Zealand	54	0.09	0.05	0.14
Taiwan	20	0.09	0.26	0.35
Japan	17	0.35	0.28	0.64
Chile	2	0.35	0.02	0.37

The average priority index value was similar for buildings in Viña del Mar (0.37%) and Tainan (0.35%), however 20% of buildings in Tainan sustained severe damage while only 2% of buildings in Viña del Mar had severe damage. This is attributed to structural walls providing greater stiffness to the structure relative to the equivalent area of columns.

Buildings in Japan had the largest priority index on average (0.64%) and the same average wall index as the buildings in Chile (0.35%). 17% of the buildings in Japan experienced severe damage compared to 3% of buildings in Chile. Without more information about the Tokachi-oki earthquake and the ground motion intensity, it is impossible to know if the earthquakes were comparable. The differences in surveying techniques may have also led to Shiga et al. (1977) focusing on structures with severe damage. Nevertheless, there is a clear trend between increasing WI and PI and a reduction in severe damage within the Japanese data. There were 24 buildings in Japan that had a priority index of less than 0.4%. Of these structures, 15 (63%) experienced severe damage. For the 80 buildings in Japan that had a priority index greater than 0.4%, only 3 (4%) had severe damage.

Bar charts were plotted using the entire data set (375 buildings) to show the relationship between frequency of damage and structural indices of the buildings (Figures 3 and 4). Figure 3a and 4a use a lower bin of < 0.20% for priority index to provide a reasonable sample size of buildings (very few buildings had a PI < 0.10%). The results illustrate that as PI and WI increase, the fraction of buildings that experience severe damage reduce. 2% of buildings with a WI > 0.20% experienced severe damage, compared to 30% of buildings with a WI < 0.20%. Similarly, 2.5% of buildings with a PI > 0.4%, compared to 25% of buildings with a PI < 0.4%. Only 1 of the 24 buildings surveyed in Christchurch had a WI > 0.20% and none had a PI > 0.40%. The results show that wall index was just as effective as priority index at identifying vulnerable structures.

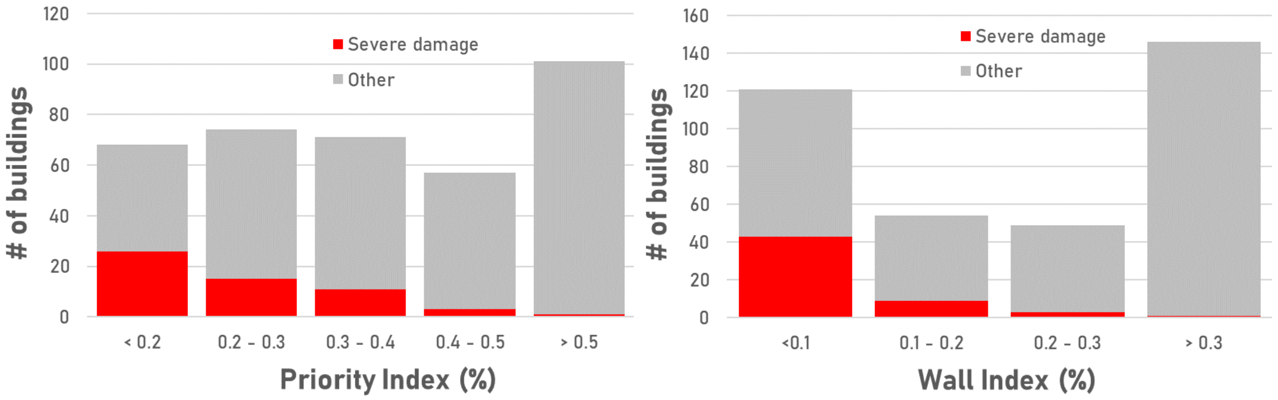


Figure 3: Priority index (PI) and wall index (WI) for all 375 buildings, and the severity of damage they experienced.

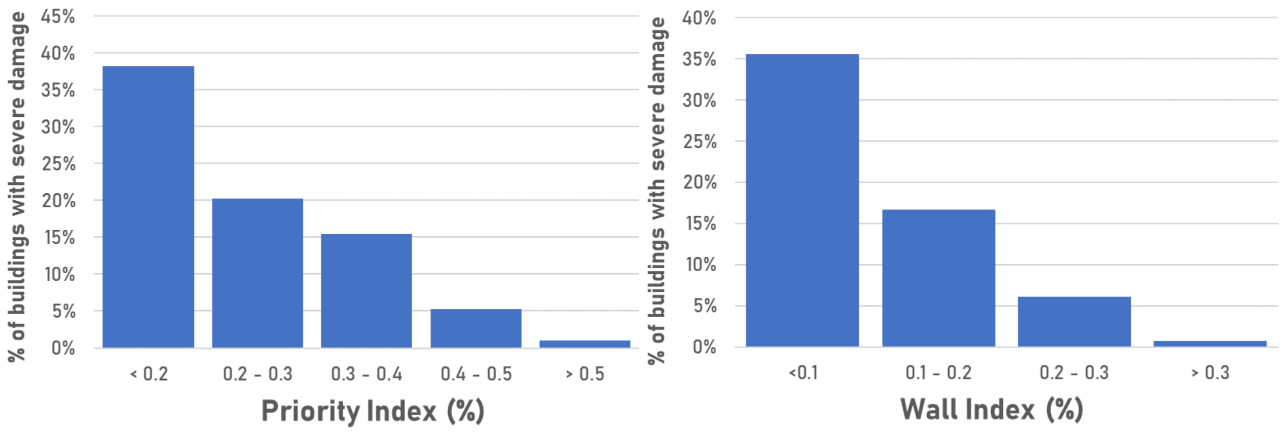


Figure 4: Percentage of buildings with severe damage vs a) priority index (%) and b) wall index (%)

5 CONCLUSION

The frequency of severe structural damage reported for 375 RC buildings after four earthquakes (Japan 1968, Chile 1985, Christchurch 2011, Taiwan 2016) was compared. Buildings were ranked in terms of wall index WI and column index CI as defined by Hassan and Sozen (1997). The highest frequency of severe damage (54%) was observed in Christchurch, where the mean value of CI+WI was the smallest in the studied sample

(0.14%). Similarly, the two higher values of WI were calculated for buildings in Chile and Japan (0.35% in both cases), where the two smaller damage frequencies were reported (2% and 17%).

Nevertheless, a place-by-place study of the plausible correlation between frequency of damage and index values may be obscured by two factors: a) differences in surveying techniques and b) differences in ground motion intensity. The survey in Chile was the broadest, the surveys in Taiwan and Japan were meant to include both damaged and undamaged buildings, and surveyors in New Zealand focused more on damaged buildings. At the same time, the intensities of motions in Chile, New Zealand, and Taiwan seem comparable within the period ranges of interest, but limited information on intensity is available for Japan.

Combining all the studied data to create a broad sample covering wide ranges of shaking intensity, building configuration, and surveying methods led to Figure 3 and 4. These plots show a clear trend suggesting that damage increased with decreasing values of both WI and WI+CI. In the aggregated sample, the frequency of damage in buildings with WI> 0.2% was 2%, while the frequency of damage in the rest of the sample was 15 times larger (i.e. 30%). This contrast and Figures 3 and 4 support the idea that stiffer structures perform better. Available literature (Algan 1982; Garcia et al. 1996) also suggests that more robust structures a) are not much more expensive, and b) protect partitions, facades, and finishes. The one tangible caveat preventing wider use of stiffer structure, other than local traditions, is the perception that contents and suspended non-structural elements perform worse in stiffer buildings. To the knowledge of the writers, no systematic, quantitative field and or laboratory evidence supports this idea, which seems to stem from isolated and or anecdotal reports. An ongoing experimental investigation is addressing this matter.

6 ACKNOWLEDGEMENTS

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