Fast prediction of the contribution of ceilings damage in the seismic loss of RC buildings

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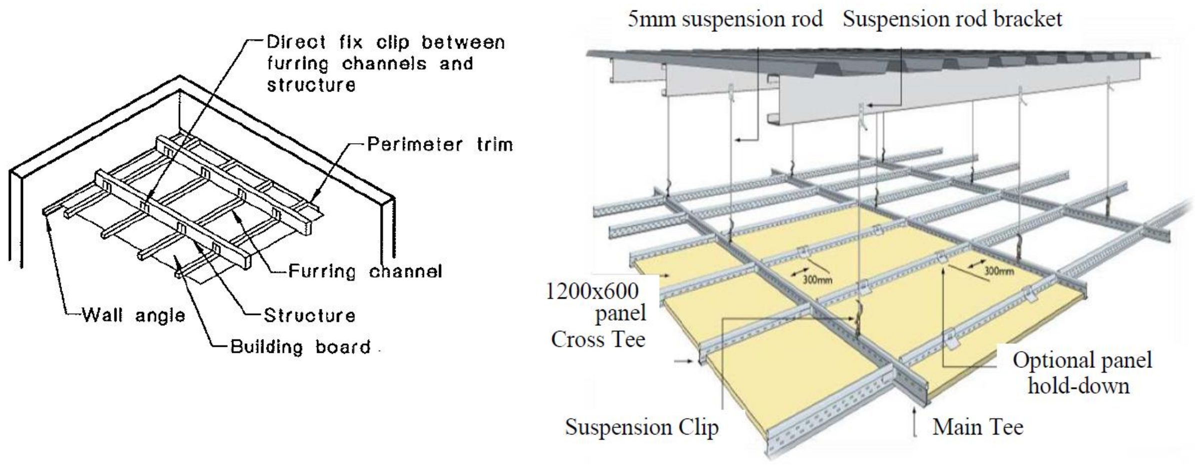
ABSTRACT: A method to estimate the contribution of damage of typical suspended ceiling to the total loss of RC buildings at a given peak floor acceleration demand is proposed in this paper. A wide range of ceiling sizes, ceiling replacement costs, and total building construction cost of RC buildings within New Zealand is collected. Based on the collected data, failure cost distribution of typical ceilings with varying dimension is generated. The fragility function for suspended ceilings of size 6mx12m is first utilized to construct a generalized fragility function for typical suspended ceilings with various dimensions. The fragility function is then combined with the cost curve and is normalized with respect to the total building cost to obtain the loss of typical ceilings at various floor acceleration demands. The resulting probabilistic loss curve provides a fast approximation of the likely loss of ceilings at various floor accelerations in typical RC frame buildings without requiring any specific information. Crudeness of the developed probabilistic method is investigated through rigorous loss assessment of ceilings of a case study RC building. It is shown that the difference between the average losses of ceilings predicted by the proposed method and the rigorous detail loss estimation method is within 5%.

1 INTRODUCTION

Experiences of past earthquakes have shown that financial implications of earthquakes due to damage in building components result in heavy burdens to the society after a major event. Financial loss of buildings following earthquakes potentially stems from damage to structural and non-structural components and contents. Earthquake reconnaissance reports of recent earthquakes (Kam et al., 2011; Wilkinson et al., 2013) have heighted the fact that even when structural damage is limited or negligible, non-structural components and contents have been the major contributors to the direct losses and downtime for majority of engineering structures. These observations are in agreement with the outcome of probabilistic seismic loss assessment of various types of buildings (Aslani & Miranda, 2005; Bradley et al., 2009; Ramirez & Miranda, 2009). As part of non-structural components, ceilings have been observed to be a dominant source of loss in non-structural components (Dhakal, 2010; Dhakal et al., 2011; Kam et al., 2010; MacRae et al., 2011).

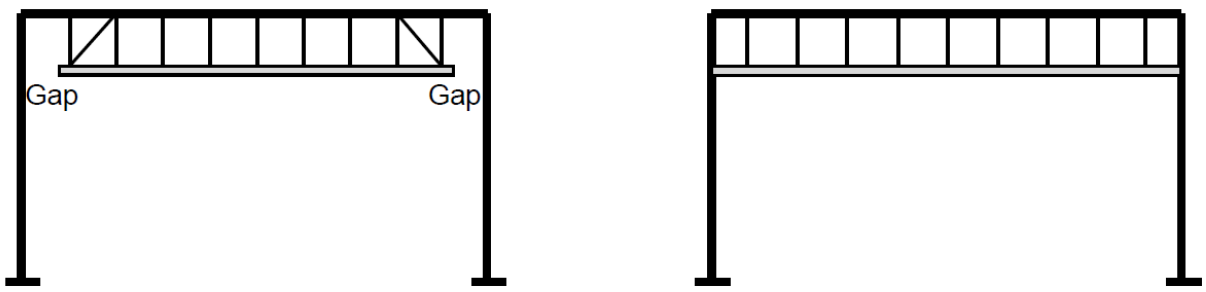
Ceilings in New Zealand may generally either be of direct fixed or suspended ceilings types (AS/NZS-2785, 2000). As depicted in Figure 1, the fixed types of ceilings are directly connected to structural elements and are comprised of gypsum plasterboards that are glued to light timber members. The suspended types of ceilings commonly consist of heavy infill panels (e.g., acoustic tiles) that are supported on a grid of steel beams. The grid beams are suspended through ceiling hangers anchored to the floor above. In New Zealand, while there is no restriction on the ceiling type that may be used in different situations, suspended types of ceilings with cold-formed steel grid (Figure 1) are the mostly used in commercial buildings.



(a) Direct fix sheeted or flush system (b) Suspended system: Two-way exposed

Figure 1. Direct and suspended ceiling systems (adopted from Dhakal et. al. 2011)

Floating and perimeter restrained ceilings are the common types of suspended ceilings used in New Zealand. Floating ceilings are braced to the floor above to prevent large movements under service conditions, as well as to transfer horizontal earthquake induced inertia forces, and these are not connected to the perimeter wall/frame as shown in Figure 2(a). On the other hand, ceilings that are restrained laterally by the walls/frames around their perimeter are called perimeter fixed ceilings. Among these common types of suspended ceilings, majority of commercial buildings in New Zealand use perimeter restrained types. As schematically shown in Figure 2(b), in perimeter restrained ceilings, the rails/tees are vertically supported to the floors and are fixed along the edges.



(a) Floating type (b) Perimeter restrained

Figure 2. Schematic illustration of perimeter restrained ceilings (adopted from Dhakal et. al. 2011)

Since perimeter restrained ceilings are connected to the floor and the surrounding walls, the acceleration induced by earthquake in these ceilings are similar to the acceleration induced in the floor. At each side of the ceiling tiles, the earthquake forces are transferred from one end to the other and are accumulated along the ceiling rails until they reach the maximum value at the other end. Paganotti et al. (2009) showed that the most critical element in this type of ceilings is the compression connections at the ceiling boundary. If the force at this point exceeds the capacity of the member and the connection, damage occurs in the ceiling system and collapse of the ceiling may take place.

Due to the remarkable contribution of ceilings in the financial loss of buildings in the event of earthquakes, prediction of the likely loss of ceilings becomes of a prime importance. To estimate the likely loss of ceilings in earthquakes, ceiling fragility functions, indicating the relationship between the floor/ceiling acceleration and failure probability of ceilings, shall be combined with the ceilings loss curves, which indicate the relationship between the failure and probable cost of the replacement of ceilings. The resulting curve is a function which relates the acceleration induced at the ceiling with the probable replacement cost. This paper aims at providing generic functions to estimate the likely loss of ceilings given acceleration at a floor level. To this end, a generic fragility function is developed through statistical simulation that considers both ceiling size and ceiling type. Then, based on the collection of a large amount of information on the replacement cost of ceilings in NZ, ceiling cost curves are combined with the generalised fragility function. The result provides an approximate generic function relating the acceleration at storey levels to the likely replacement cost of ceilings. The proposed generic function presents a rapid tool for approximate estimation of the probable loss of suspended ceilings without requiring the information on the parameters involved in prediction of the loss of ceilings. At the end, the crudeness of the proposed function is validated through the ceiling loss assessment of an example case study building.

2 GENERALIZED FRAGILITY FUNCTION FOR TYPICAL CEILING SYSTEMS

This section aims to provide a generic fragility function which, at any size of ceilings, relates probability of failure to the floor acceleration as the engineering demand parameter for ceilings. To construct a generic fragility function for ceilings in this research, the fragility function for $12m \times 6m$ size ceilings proposed by Paganotti et al. (2009) is used as a benchmark to obtain fragility functions of ceilings with different sizes. Distribution of typical ceiling sizes as well as distribution of the longer side length of ceilings in typical office buildings is estimated. By combining the distribution of longer side length of ceilings with the fragility function obtained for a longer side of 12m, i.e. the benchmark fragility function, generalized fragility functions at any ceiling size can be generated. The following paragraphs describe details of this process.

Distribution of the size of ceilings has to be first estimated as capacity of ceiling systems is related to its size. Rather than size of a single ceiling tile, in this context, the ceiling size refers to the total length of ceilings continually connected through grid of ceiling elements. Therefore, assumptions can be made that the ceiling sizes are equal to the size of rooms and that the ceilings are fixed to the edges. These assumptions imply that the distribution of room sizes provides the distribution of ceiling sizes. To obtain the distribution of room sizes, a library of drawings for office buildings in Christchurch central business district (CBD) was collected. From the drawings, the area of the rooms in the buildings was measured. Based on the data set of 725 measured rooms within the buildings in Christchurch CBD, cumulative distribution function of room area, assuming a normal distribution, was generated and is shown in Figure 3. This figure indicates that only 25% of the rooms have an area of less than $20m^2$. The large area of rooms in this figure originates from the fact that the data has been collected from the office buildings where rooms are generally large in size.

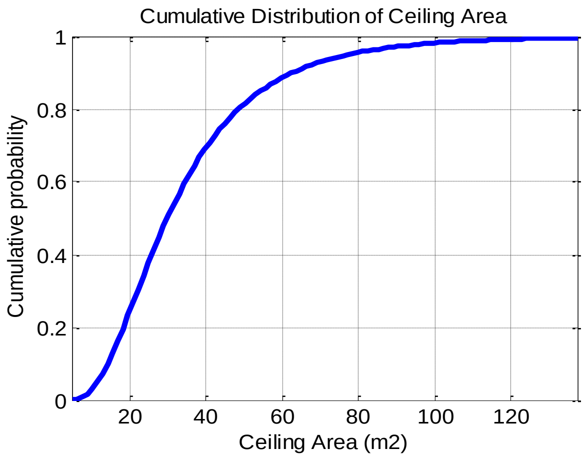


Figure 3. Cumulative Distribution Function of ceilings area

It is noted that majority of the rooms in buildings are square in shape, and hence, if the same acceleration is applied to the room in both directions, the longer side of the room produces greater forces. In other words, the longer side of the ceilings is the critical direction if a ceiling is subjected to similar accelerations in both directions. Consequently, in addition to the distribution of ceilings area, distribution of the longer side length of ceilings is also required. To obtain the distribution of longer side length of ceilings in buildings, aspect ratios of the studied rooms were measured and distribution of the aspect ratio of the studied rooms was generated which is shown in Figure 4.

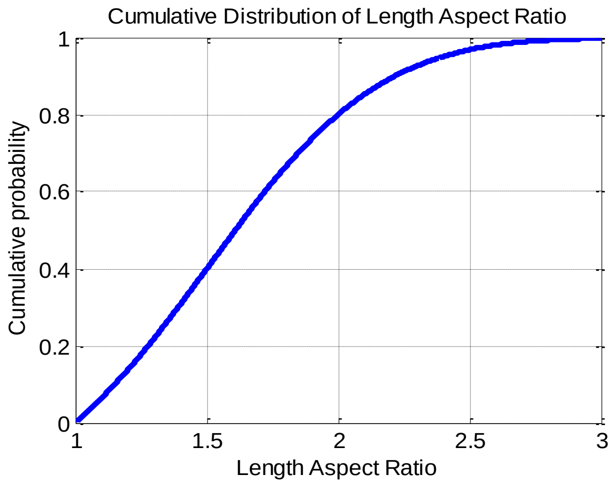


Figure 4. Cumulative Distribution Function of the ceilings longer to shorter side length

Having the area and the longer/shorter side aspect ratio of rooms, the longer side of rooms can be obtained by $L_L = \sqrt{A \times \alpha}$ $L_L = \sqrt{A * \alpha}$, where, A is the area of rooms and α is the aspect ratio. Since the area and the aspect ratio in this equation follow a probabilistic distribution, Monte Carlo simulation was used to combine the two distributions and generate the distribution of the longer side length of ceilings. The resulting distribution of the longer side of ceilings is depicted in Figure 5.

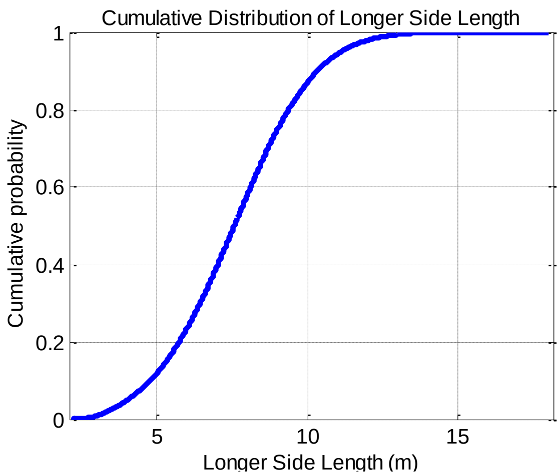


Figure 5. Cumulative Distribution Function of the longer side length of ceilings

In this research assumption is made that the capacity of ceilings has a linear relationship with their longer side length. This assumption is based on the ceiling experiments of Paganotti et al. (2009) which tested typical elements and connections of suspended ceiling systems and proposed fragility functions for ceilings with three different sizes in the longitudinal direction. Their findings suggest that the failure probability of ceilings is directly related to the size of ceilings and by increasing the number of tiles, i.e. increasing the ceiling size, probability of failure increases, approximately by a linear relationship. In other words, the acceleration capacity of ceilings decreases linearly by increasing their longer side length. Therefore, knowing the failure probability of ceilings with longer size of 12m at a given acceleration (from Paganotti et al. (2009)), the failure probability of ceilings with different sizes at the same acceleration can be calculated. Generalising this interrelationship, the converted acceleration capacity of ceilings with a longer length of L, a_{conv}, can be obtained by the following equation:

$$a_{conv} = \frac{12m}{L} \times a_{12m} \quad (1)$$

where a_{12m} is the acceleration capacity of a 12m long ceiling system. Once again, as the longer side length of ceilings follows a statistical distribution, Monte Carlo analysis was performed to obtain the distribution of the converted accelerations. For a given acceleration such as 0.1g, a random value of longer side length conforming to a normal distribution was generated. The corresponding converted ceiling capacity was then calculated using Equation 1. By using the benchmark fragility curve, corresponding probability of failure can be obtained. The procedure was repeated to get multiple results. The median failure probability of the ceilings subjected to a given floor acceleration was then obtained by taking the average value of the data set. The procedure was repeated for various accelerations and the resulting generic median failure probability of ceiling systems regardless of the size is shown in Figure 6. The figure indicates that probability of ceiling failure becomes immediately significant at near-zero accelerations; this is partly a by-product of the probabilistic derivation process and partly due to the vulnerability of large sized ceilings even at small accelerations. It is noted that failure of ceilings in this context refers to the state in which the ceiling rails supporting the tiles fail at one point. This failure yields to the falling of some of the ceiling tiles. At this state, damage to the ceilings is to the extent that cannot be repaired and replacement of the ceilings is required.

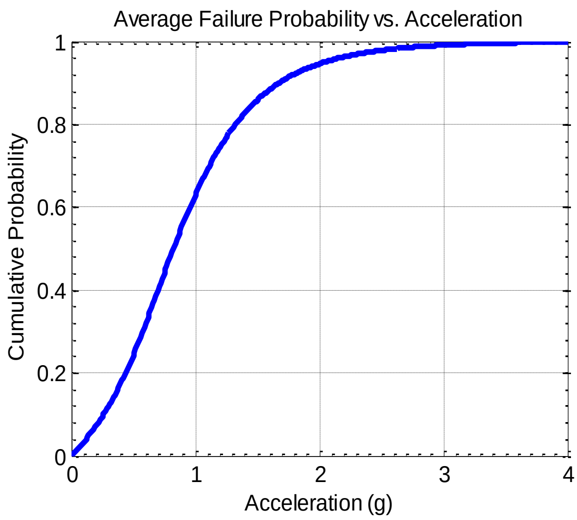


Figure 6. Generalized fragility function of typical suspension ceilings

3 GENERIC REPLACEMENT COST FUNCTION FOR TYPICAL CEILINGS

This stage of the research aims to construct a generic function which indicates likely replacement cost of typical ceiling systems subjected to a given acceleration. To achieve this, information on the replacement cost of various types of ceilings with different configurations was collected. The information on the replacement cost of ceilings was obtained from local builders, some of the ceiling suppliers in New Zealand (Armstrong™ and USG™), from employees of construction companies, and the price range on Rowlinson's construction handbook. Based on the collected data, the median and standard deviation of ceilings replacement cost per square meter area of ceilings was amounted to $\mu_{cost|Failure} = \$93.48\ NZD/m^2$ and $\sigma_{ceiling} = 5.83\ NZD/m^2 \sigma_{ceiling} = \$5.83$, respectively. Monte-Carlo simulation can be used to combine the median replacement cost of ceilings per square meter with the probability of failure of ceilings at a given acceleration. Using Monte-Carlo simulation, the median, 16th percentile, and 84th percentile of the replacement cost of ceilings at various accelerations were obtained and are shown in Figure 7.

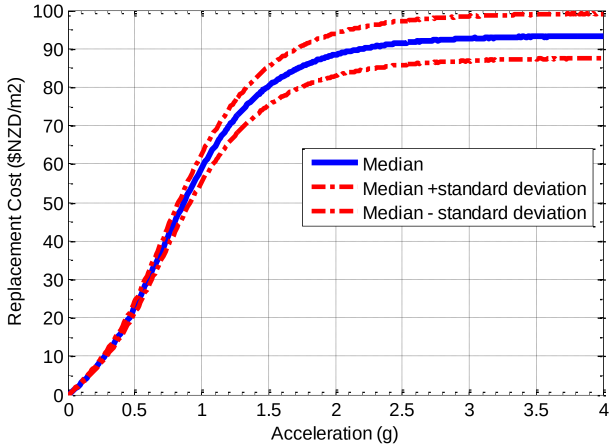


Figure 7. Generic loss curves of typical ceilings at various accelerations

This figure presents a graph showing the median replacement cost of ceilings at various accelerations considering the likelihood of failure of ceilings at a given acceleration. The estimated loss shown in this figure is independent of the room size, the type of ceilings, and longer side length of ceilings and can be used for various applications. However, the cost shown in this graph is obtained based on the data collected in New Zealand and Christchurch city in particular. Therefore, it may not be directly applicable for other locations due to variation of prices in different places. In order to be able to generalize the curve, the curve can be normalized with respect to the total cost of office buildings per square meter of floor area. By collecting the information of a vast number of office buildings in Christchurch CBD, the median and variation of total building construction cost was estimated as $\mu_{building} = 2034.19\$NZD/m^2$ and $\sigma_{building} = 212.97\$NZD/m^2$, respectively. It is noted that the data used to obtain this result is from the construction cost of office buildings in Christchurch CBD. Majority of the buildings in this research are medium-rise buildings within a range of 5-10 storeys. Therefore, the dispersion of the cost might have been increased if more variety of buildings height were considered to collect the information.

Since the total construction cost of buildings is probabilistic, Monte Carlo simulation was performed to normalize the unit cost of ceilings with respect to the total building cost. The resulting normalized replacement cost of typical ceiling systems with respect to the total cost of building construction is shown in Figure 8. Depicted in the figure are also the median and $\pm$ one standard deviation of ceiling replacement cost. Knowing the acceleration induced at each storey level, this figure provides a fast prediction of the loss of ceilings regardless of their size and type and without requiring any information regarding the fragility of ceilings. As can be seen in the figure, the median loss of ceilings with respect to the total building cost is around 4.5% for large accelerations for which the failure probability of ceilings is high.

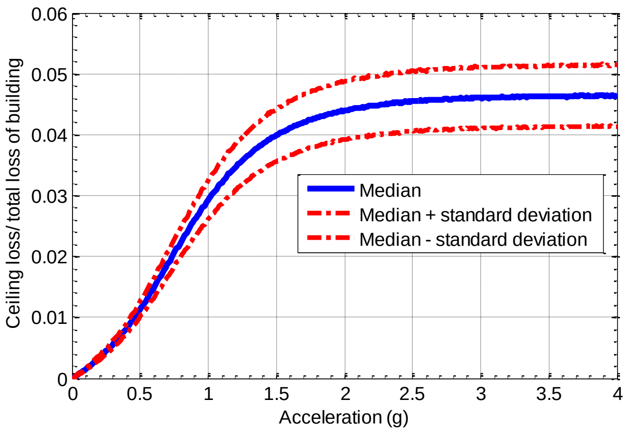


Figure 8. Normalized generic loss curves of typical ceilings at various accelerations

4 COMPARISON TO CASE STUDY BUILDING

To examine the accuracy of the proposed generic acceleration-loss function proposed in previous section, repair cost of a case study building is directly computed through a rigorous approach and compared with the proposed approximate method. The case study building is the engineering building of the University of Canterbury. The engineering building at the University of Canterbury is an RC building consisting of five floors. Several lecture rooms, self-study rooms, and CAD rooms for undergraduate students are located at the first and second floors. Postgraduate research rooms and a large drafting room are located on the third floor. The fourth and the fifth floors of the building are used as offices for academic staff. The area of each storey level is around $1680m^2$.

Since the detailed architectural and structural drawings for the case study building were available, a detailed and reasonably accurate estimation of the loss due to the failure of ceilings with respect to the total cost of the building can be performed. As the ceilings' area and longer side length are known, the uncertainty due to these variables is omitted in the estimation. Hence, the ceiling cost is the only variable which contains uncertainty. The first step in the assessment of loss is prediction of engineering demand parameters, i.e. floor accelerations in this case. To estimate the floor acceleration at each storey level, the equation stipulated in NZ seismic code (NZS1170.5, 2004) is utilized. NZS 1170.5 provides an approximate equation for calculation of accelerations at each storey level depending on the site soil condition and the selected return period of the earthquake.

Once the accelerations at each storey level are calculated, the following steps are performed at each storey floor to assess the loss of ceilings for the case study building.

1. Measure the longer side of rooms;
2. Define intervals of longer side length of rooms and classify the rooms according to their longer side length;
3. Calculate the median value of longer side length;
4. Measure the shorter side length of rooms in each class of rooms and define shorter length intervals;
5. Sub-classify the rooms according to their shorter side length;
6. Count the number of rooms at each class of rooms;
7. Using to the median value of longer side length calculate the converted acceleration capacity of the ceilings (Eq. 1);
8. Estimate the failure probability of each class of ceiling using the fragility function for ceilings with $6 \times 12m$size,
9. Multiply the failure probability by ceiling area, number of rooms and ceiling replacement cost to obtain the estimated loss of each class of rooms;
10. Repeat the procedure for all rooms, obtain the total ceiling replacement cost;
11. Divide the total cost by the total area of the ceiling to obtain the average unit replacement cost;

The above steps were repeated for all five floors in the building. As an example, the estimated values at each step are shown in Table 1 for the fourth floor of the case study building at the design level earthquake (500 years return period). As can be seen in the table the average loss associated with ceilings is estimated as NZ$28.68 per square meter area of the floor.

Alternatively, ceiling losses can be estimated using the graphs obtained in previous sections for the acceleration corresponding to the design level of earthquake. Figure 9 shows a comparison of ceiling loss by the approximate method and the detailed loss assessment for the case study building from six different return periods. Rather than showing the median value of the ceiling loss predicted by the proposed approximate method, a range of values between the 5% to 95% confidence intervals are highlighted. It is evident that ceiling losses in the case study building falls within the 95% interval of the approximate method for most of the return periods. The results of the case study building are generally lower than the median value of the approximate method indicating conservative predictions of the approximate method. It can also be seen that the case study results tend to get closer to the case study as the return period increases. For R=25 years and R=50 years, the exact ceiling loss in the third floor is higher than that given by the method developed in the paper.

Table 1. Ceiling replacement cost calculation of 4th floor of engineering building

Longer Length (m)	Median Longer (m)	Shorter Length (m)	No. of Rooms	Area m^2	Total Area m^2	Failure Probability	Total Loss ($NZD)
2 to 4	3	1.5 to 2	7	5.25	36.75	0.087	$299
	3	2 to 3	40	7.5	300	0.087	$2,440
5 to 6	5.5	2 to 3	0	0	0	0.184	$0
	5.5	3 to 4	0	0	0	0.184	$0
	5.5	4 to 5	24	24.75	594	0.184	$10,217
	5.5	5 to 6	0	0	0	0.184	$0
10 to 11	10.5	2 to 3	0	0	0	0.503	$0
	10.5	3 to 5	0	0	0	0.503	$0
	10.5	5 to 6	13	57.75	750.75	0.503	$35,272
	10.5	6 to 7	0	0	0	0.503	$0
	10.5	7 to 11	0	0	0	0.503	$0
			Total ceiling area		**1681.5**	**Cost**	**$48,227**
						Average	**$28.68**

This difference at the third floor stems from a large amount of open spaces (the drawing room) on the third floor, which has a very large longer side length of ceiling compared to the median value of longer side of rooms. However, the close agreement of the median loss from the approximate method with the detail loss calculated for the case study building suggests an acceptable accuracy of the proposed graphs.

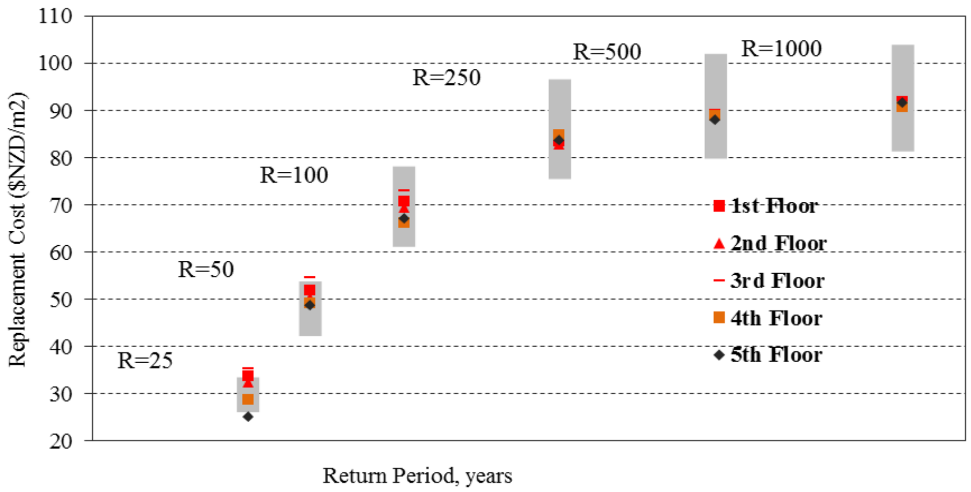


Figure 9. Comparison of the estimated loss of ceilings of the case study building with the approximate method

5 CONCLUDING REMARKS

In order to estimate the loss of typical suspended ceiling systems in buildings subjected to a given floor acceleration, a methodology was developed by collecting a large set of ceiling size and cost data and conducting a series of Monte Carlo simulations. Generalized loss curve indicating the relationship between the floor acceleration and probable loss of suspended ceilings was proposed. In a typical RC office building, it was observed that the ceiling replacement cost can take up to 5.5% of the total building construction cost. It is expected that the results presented in this paper provide a useful tool for fast prediction of the suspended ceiling losses without requiring any information on the type and size of the ceiling. The results are subject to significant uncertainty and research is continuing to fine tune the tool and assess epistemic uncertainties. The outcome can facilitate estimation of seismic loss of buildings for future generation of performance-based seismic design guidelines which may use seismic loss as a key parameter for decision making.

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