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Functionality measures for quantification of building seismic resilience index

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ABSTRACT

In recent years, the topic of resilience has caught the attention of the structural engineering community. Several approaches have been proposed through the years to quantify resilience for various infrastructure systems, but quantifying the resilience of buildings, and groups of buildings, remains challenging. Here, research was conducted to investigate the effectiveness of three different approaches proposed to quantify resilience. The proposed approaches use repair costs, occupancy levels, and asset values as the functionality measures to quantify resilience. Resilience indexes are quantified for four different example buildings using the three approaches. Performance-based assessments of the buildings are performed following the procedures of the Federal Emergency Management Agency (FEMA) P-58 document using an intensity-based method and the simplified analysis procedures. The proposed methodology by the Resilience-based Earthquake Design Initiative Rating System (REDi), to account for downtimes due to delays calculated from the FEMA P-58 assessments, are incorporated in the resilience quantification for the four example buildings. The delays due to downtimes are included in the computation of resilience index considering two scenarios based on different impeding factors. Of the approaches considered, using the occupancy level approach, with due consideration of the collapse probabilities, was deemed to provide a more meaningful expression of building resilience.

1. Introduction

The term "community seismic resilience" was coined nearly two decades ago when proposed together with a framework to quantify resilience as a function of the ability to restore functionality following a disaster [1]. Since then, research on the topic has grown exponentially. Resilience quantification for lifelines and networks, have been performed extensively [2]. This is in part due to the fact that the functionality of most distributed systems is often well-defined and thus easy to quantify, be it electricity, gas, or services provided to customers. However, for the structural engineering community, the quantification of resilience for buildings has been challenging. For physical infrastructures that are not serving a specific network, the definition of a unique functionality measure is a complex problem [3]. Existing resilience frameworks [4–7] have provided generic measures to quantify the resilience of individual buildings. Various approaches have been proposed [8]; some are conceptual (e.g., [4,9,10]), others focus on traditional demand engineering parameters (e.g., [11,12]). Comprehensive summaries on the breath of contemporary research on disaster resilience have been provided by multiple authors (e.g., [13–15]), and extensive work on the development of fragility curves for various structural systems and types of buildings have provided key building blocks in support of resilience framework (e.g., [16,17]; to name a few) and for implementation in various computer platforms, such as [18,19], and others. However, in a simpler perspective, focus here is on resilience as a single quantifying index for given buildings.

Structural engineers, by training, endeavor to ensure satisfactory seismic behavior of the structural system and – sometimes – of non-structural components when damage to these components can entail considerable costs [20]. Therefore, structural engineers are familiar characterizing performance in terms of story drift ratios, or floor accelerations/velocities, as these are engineering parameters that have been used in the performance assessment of structural and non-structural systems, but the quantitative linkage from those measures to functionality remains a core problem when quantifying resilience [21].

One of the hurdles in quantifying resilience from the perspective of individual buildings has been the challenge of obtaining actionable

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resilience values, i.e., values that are both meaningful, consistent with expectations from an engineering judgement perspective, and highlighting the factors that will impact community resilience on the basis of its inventory of buildings. For example, a resilience quantification of buildings based on functionality measures should demonstrate that mitigating the initial loss of functionality can help achieve a faster recovery and greater resilience [3].

To achieve the above goal, the definition of a performance measure to express building functionality from a resilience perspective, in a manner that can be tracked over time, is required. The definition of the functionality measure should consider its variation through time and space. The ability to quantitatively measure building resilience in such a way would provide an important tool for stakeholders in a community that desire to improve resilience to natural disasters.

The work presented here investigates how different potential functionality measures can be used to quantify building resilience indexes. The considered functionality measures are repair cost, occupancy level, and asset value. Resilience indexes are calculated and compared for four different buildings. Suitability of different functionality measures in characterizing resilience is evaluated and discussed, which is helpful to gain valuable insights on some aspects of resilience quantification. This is important in the perspective that resilience measures must convey a "message" that is truthful to its implications and consistent with expectations, which may not always be the case depending on how resilience is computed. The quantification of building resilience, by itself, cannot capture all the aspects of a complete community resilience framework, but it provides an important piece that is needed to contribute to more "unified" resilience frameworks.

2. Theoretical background and study setup

2.1. Resilience concept

Conceptually, resilience can be quantified computing the area under a functionality curve, shown in Fig. 1, between times t_0 and t_1. In Fig. 1, the vertical axis measures the system's performance (expressed by a functionality measure), which drops from 100% (considered to be correspond to the condition under normal circumstances) to a certain level at time t_0. Functionality is eventually recovered at time t_1. It could be observed that the drop in functionality at time t_0 is sudden here, because it corresponds to the case of damage due to an earthquake. This drop can be less sudden for other functionality measures or other hazards. Additionally, the target recovery level considered at time t_1 is often a return to pre-earthquake condition level, but it can also be lower or higher levels than that [22].

2.2. Building descriptions, adopted methodologies, and expected demands

Four different buildings are considered here. Each building is different from the others in dimensions and structural lateral load resisting system, as seen in Table 1, where Buckling-Restrained Braced Frame (BRBF), special moment frame (SMF), reinforced masonry (RM), and unreinforced masonry (URM) are respectively used for the four buildings. Additionally, the first column in Table 1 lists the nomenclature that is used for each building. For example, Building (1) is used throughout to refer to the steel BRBF building. The buildings are located in Los Angeles, California. A Site Class D soil profile [23] with an expected shear wave velocity of 259 m/s was assumed.

The procedure for an intensity-based assessment from FEMA P-58 was followed to define the demand for each building. Two-dimensional linear models, consistent with the procedures of ASCE/SEI 41-17 [24] for modeling the strength and stiffness of typical building elements, were assembled and evaluated using the software SAP2000 [25]. Pushover analyses and collapse vulnerability assessments were evaluated for each building using SAP2000. The performance of buildings as well as structural and non-structural components was characterized as a function of story drift ratios and acceleration.

The structural designs of the buildings are intended to represent typical buildings in an existing community. The purpose here was to have examples of different construction types in a city block, and to evaluate resilience indexes based on the seismic response of such buildings. More information about numerical modeling and engineering demand parameter calculations can be found in [26].

Here, for the purpose of quantifying resilience for individual buildings, two tools were used. First, the methodology presented in the "Seismic Performance Assessment of Buildings" (FEMA P-58) [27] was followed to develop a repair schedule to bring back a building to its pre-earthquake condition. The FEMA P-58 methodology has been implemented in the Performance Assessment Calculation Tool (PACT) that is used to construct Building Performance Models. Loss calculations in PACT are performed for a given "realization" in the Building Performance Model. A "realization" is a single loss analysis with a set of generated inputs (i.e., date, time, demand, list of elements susceptible to damage, etc.). Examination of the Building Performance Model allows the user to study the loss analysis results for different realizations, and based on different measures (e.g., repair time, repair cost).

Second, to consider delays (a.k.a. impeding factors) that can be incurred before the initiation of repair works, due to factors such as permitting, financing, inspections, among others, the Downtime Assessment Methodology [28] was used. This methodology uses "Repair Class" to characterize the extent of damage for the components defined

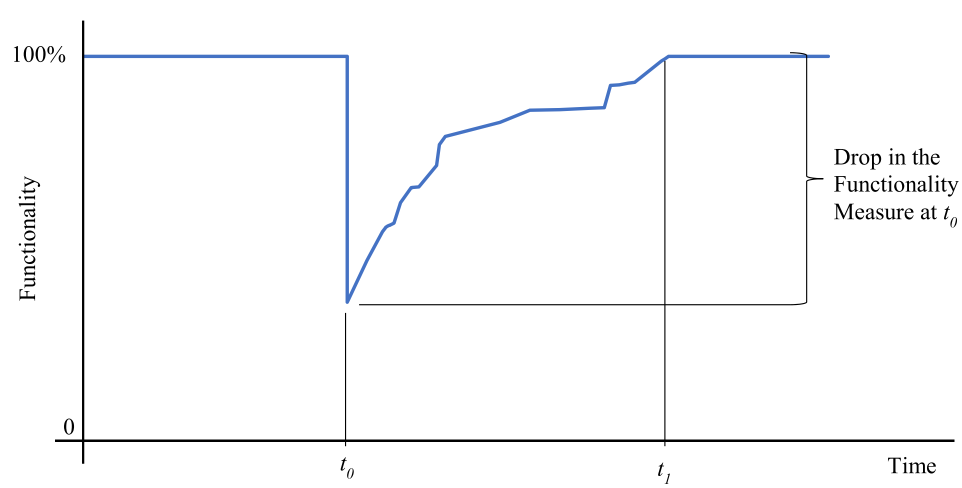

Fig. 1. Measure of Seismic Resilience [1].

Table 1
Nomenclature and Properties of the Four Example Buildings.

Building	Construction Material	Structural System	Dimensions		Floor Height			
			L	B	h_1	h_2	h_3	h_4
(1)	Steel	BRBF	162 ft (49 m)	162 ft (49 m)	12 ft (3.7 m)	12 ft (3.7 m)	12 ft (3.7 m)	
(2)	Reinforced Concrete	SMF	120 ft (37 m)	180 ft (55 m)	15 ft (4.6 m)	13 ft (4.0 m)	13 ft (4.0 m)	13 ft (4.0 m)
(3)	Masonry	RM	85 ft (26 m)	85 ft (26 m)	12 ft (3.7 m)	12 ft (3.7 m)		
(4)	Masonry	URM	120 ft (37 m)	120 ft (37 m)	15 ft (4.6 m)	12 ft (3.7 m)		

in the Building Performance Model. Two scenarios were defined to consider the effect of impeding factors. Table 2 summarizes the assumed parameters for arbitrary examples of the best- and worst-case scenarios, referred here to as Option 1 (worst scenario) and Option 2 (best scenario), for the four example buildings. The building type for both options is taken as non-essential facility, given that the four example buildings are office buildings. All other parameters vary for the two options. The defined best and worst scenarios are predicated on the pre-existence or absence of a building occupancy resumption program (BORP), of contractual agreements with design engineers and general contractors, available financial options, and the highest Repair Class for structural and non-structural components obtained after the evaluation of the Building Performance Models (assumed both as 3, the maximum value).

The Downtime Assessment Methodology [28] also establishes typical Repair Sequences to address the limitation of the FEMA P-58 methodology have regarding labor allocation and the sequence of repair works. Repair Sequences A and B are defined for interior and exterior repairs, respectively. Likewise, Repair Sequences C, D, E, and F are assigned to mechanical, electrical, elevator, and stair repairs, respectively.

The Building Performance Model considers both structural and non-structural components. PACT requires an input for structural elements that are vulnerable to damage by earthquake-induced deformations, such as connections, braces, beams or columns, among others. Those structural elements are grouped in terms of the structural materials (e.g., steel, concrete, wood, etc.), configurations (e.g., different height for reinforced concrete shear-walls or different weight for steel braces), and type of structural system (e.g., special and ordinary concentric braced frames). Non-structural components consider a range of configurations and material variations for different vulnerable elements ranging from exterior curtain wall systems to desktop electronics. The inclusion of structural and non-structural components in the Building Performance Model is performed through the selection of Component Fragilities that best reflect the considered elements in the buildings.

Two seismic demand scenarios were defined. The first scenario corresponds to the design-level earthquake with a return period of 475 years or a 10% probability of exceedance in 50 years. Given the site's latitude and longitude, building fundamental periods, and site class, the 5% damped spectral accelerations (S_a) at each building's fundamental (first mode) periods ($S_a(T)$), and peak ground acceleration (PGA) were determined. The second scenario considered the simplified analysis procedures of FEMA P-58 to generate the demand input for the Building Performance Models, and it was used to observe resilience curves for each building, as will be presented later. The second scenario follows the same methodology than the first one, but was applied to several S_a, namely, 0.1 g, 0.5 g, 1.0 g, 1.5 g, and 2.0 g, and its objective was to analyze how the resilience indexes for each building varies as a function of the expected S_a. A flowchart describing the methodology followed in this work is presented in Fig. 2.

Table 2
Assumed Parameters for Impeding Factors for the Four Example Buildings.

Impeding Factor	Option 1	Option 2
Building	Non-Essential Facility	Non-Essential Facility
BORP or Equivalent	No	Yes
Financial Condition	Private Loans	Pre-arranged Credit Line
Engineering	No Engineer	Engineer on Contract
Contractor	No Contractor on Contract	Contractor on Contract
Weeks for Long-Lead Components:	12	4

3. Repair cost and occupancy level approaches

3.1. Theoretical concept and resilience curves for the four example buildings

The first expression of functionality considered here to define resilience is repair costs, as conceptually illustrated in Fig. 3(a). In this case, the maximum repair cost of the building would correspond to the cost to completely reconstruct such building. To be able to compare this maximum repair cost (that represents the functionality measure at 100%) to the repair costs obtained from PACT, an estimated maximum possible repair cost for each building should be derived from the same source, that is PACT in this case. To obtain the mentioned estimated maximum repair cost, from the Fragility Database included in FEMA P-58-3 [29], the highest values of demand parameters (story drift ratio and accelerations, assumed to produce the highest damages in each component, and therefore, represents the highest repair costs) were obtained and input in Building Performance Models for each building considering both 500 and 1500 realizations. The maximum repair costs for the components were obtained from those models (as a higher number of realizations increases the chances of obtaining higher levels of damage in building components), and defined as the estimated maximum repair cost for each component.

In Fig. 3(a), point A denotes the occurrence of an earthquake, which results in the observed drop in the property value. The time lapse from points A to B denotes the downtime due to impeding factors that hinders the initiation of repair works. Following point B, the repair works begin, and the property value increases through time (i.e., considering that it is progressively "recovered" through repairs). This increase goes up to point C, at which the property is assumed to have recovered its value, and is back to normal conditions. Additionally, it should be mentioned that some repair works (i.e., from points B to C) could require long-lead components that can further delay the repairs. Those long-lead components are components that, in normal circumstances, are not readily available (generally, mechanical equipment and custom-made components).

The second expression of functionality considered here to define resilience is the occupancy level in the building after the seismic event. It was assumed here that the occupancy for all the example buildings considered is consistent with the definition for "commercial offices". Note that the objective here is not to contrast resilience across various types of buildings, but rather to assess the significance of various functionality measures to quantify resilience using an arbitrary sample of

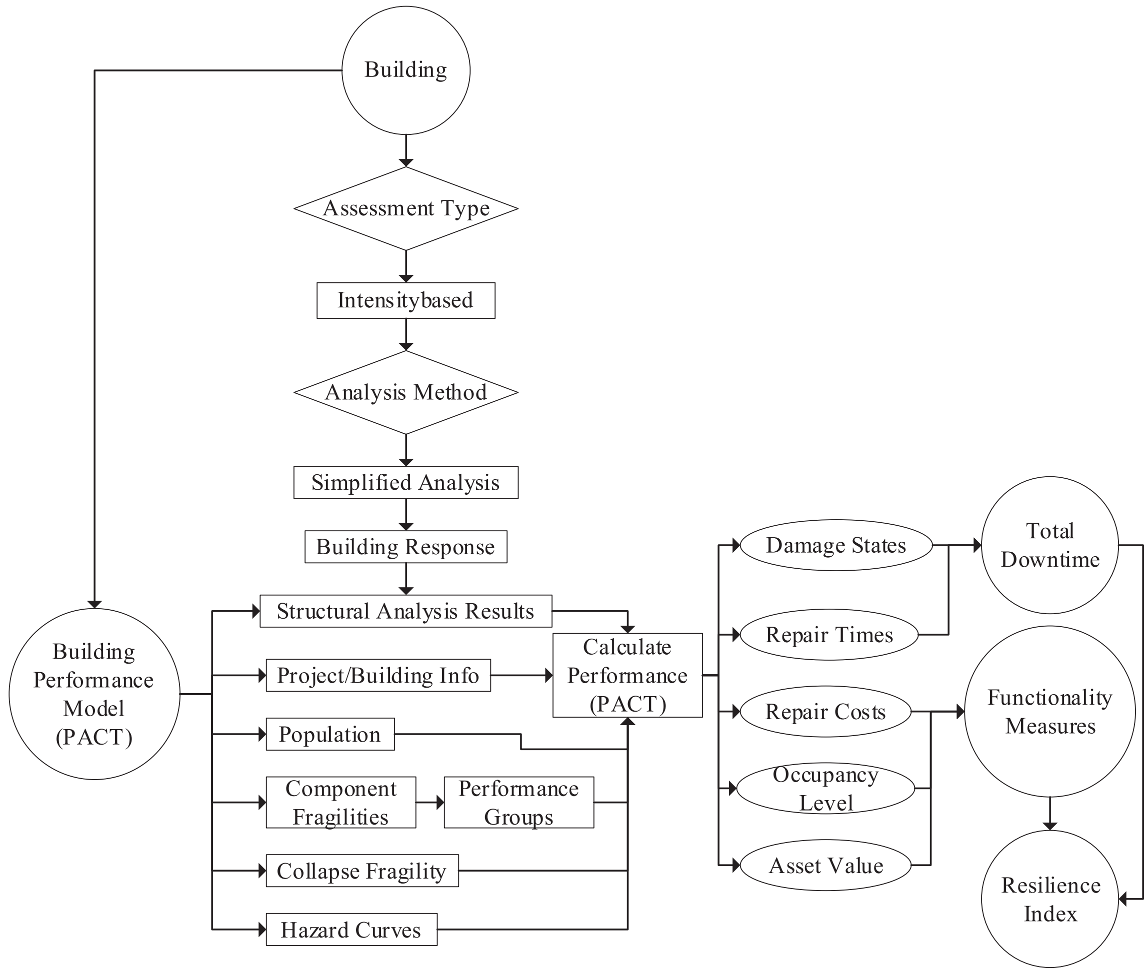

Fig. 2. Methodology to Obtain Functionality Measures and Quantify Resilience Index for a Building.

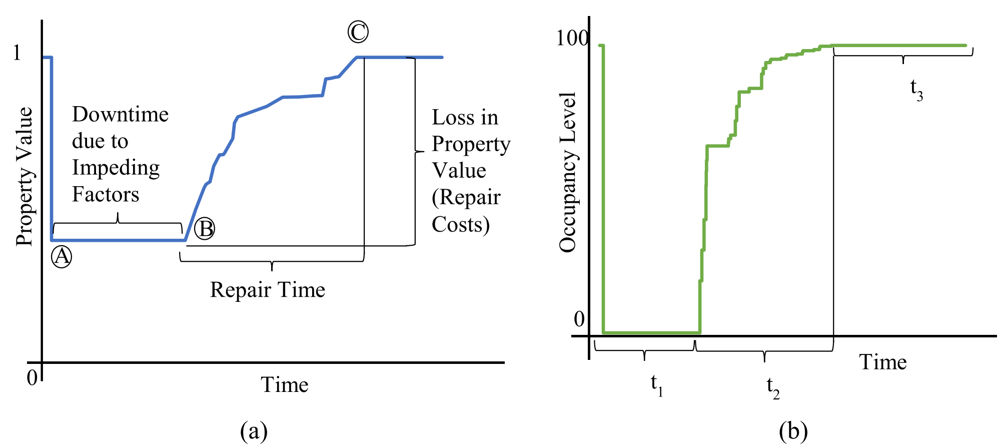

Fig. 3. Concept Curves for Seismic Resilience based on: (a) Repair Cost, and; (b) Occupancy Level.

buildings, namely commercial buildings in this case. Evidently, it is not meant to imply that all buildings in a community would be commercial buildings. Thus, the occupancy level is defined as the percentage of regular employees/users of the building that can return there under certain conditions compared to the normal operating condition before the seismic event. This refers to the fact that the recovery state can be either Re-Occupancy, Functional Recovery, or Full Recovery, or the same, Repair Classes 3, 2 or 1, respectively, as is defined in the Downtime Assessment Methodology [28]. A Re-Occupancy state is achieved when Class 3 repair works are finished, Functional Recovery when Class 2 and 3 repair works are completed, and Full Recovery when all the repair works (Class 1, 2 and 3) are finalized. The occupancy level percentages corresponding to completion of the different repair works for each of the Repair Classes were assumed as follows: completing all Repair Class 3 tasks implies achieving an occupancy level of 50%, completing all the Repair Class 2 tasks provides an additional occupancy level of 40%, and, finally, completion of the Repair Class 1 tasks brings the remaining 10% of occupants, to reach the 100% occupancy level. It was also assumed that structural repair works that have Repair Class 3 tasks did not add to the occupancy level because it was believed that these repair works must be entirely completed to ensure occupant safety and structural integrity.

To facilitate the understanding of the results presented for the occupancy level approach, Fig. 3(b) presents three variables: t_1 refers to the downtime due to impeding factors, t_2 refers to the time required to go from 0% to 100% occupancy level, and t_3 refers to the time from the conclusion of repair works to the reference time used in the analysis. The variables t_1 and t_3 define how much time a building is at the 0% or 100% occupancy level, respectively, for computation of the resilience index, while t_2 defines the required repair time.

3.1.1. Repair cost measure of functionality

Resilience curves (with repair cost as a measure of functionality) for structural and non-structural components for the two options listed in Table 2, are shown in Figs. 4(a), 5(a), 6(a), and 7(a) for Buildings (1), (2), (3), and (4), respectively. For Building (1), it can be observed in Fig. 4(a) that once repair work starts, both restoration curves for Options 1 and 2 are identical. As such, the resilience curves only differ by a "shift" and the delay time imposed by the impeding factors (prior to start of the repair work) is the only factor that shifts the restoration curves. For Building (1), the delay produced by long-lead components, which is 250 days for Option 1 and 78 days for Option 2, affected both options because the steel buckling-restrained braces needed for the structural repairs of that building, in both cases, is a long-lead component. As a product of such delay, the structural repair works concluded in approximately 264 days for Option 1 and 92 days for Option 2, after the seismic event, whereas the structural repair work itself required approximately 14 days for competition. At this point, after the structural repair works are completed, non-structural repair works begins and requires approximately 57 days to conclude, which adds up to 321 days for Option 1 and 149 days for Option 2, for the total completion of repair work after the seismic event. The costs associated with the repair works reached 679 thousand dollars for structural repairs and 1.569 million dollars for non-structural repairs, with a ratio of non-structural versus structural repair costs of about 2.3.

On the other hand, for Building (2), it can be observed in Fig. 5(a) that the delays produced by long-lead components only affected Option 1. Also, the structural repairs times are identical and total repair times only differ by the length of the impeding factor gap, which is 166 days for Option 1 and 77 days for Option 2. However, the non-structural repairs exhibit considerable differences. Those differences are attributed to the fact that the delay produced by some long-lead components completely stopped the non-structural repair works for Option 1 at Building (2), and only after the long-lead components were dispatched, could these non-structural repair works proceed. In this case, the structural repair works were finished approximately 191 days for Option 1 and 102 days for Option 2, after the seismic event, since these repair works required around 25 days to be completed. From this point, the non-structural repair works required approximately 113 days for Option 1 and 54 days for Option 2 to be completed, with completion of all repairs in 304 days for Option 1 and 156 days for Option 2. The time gap of 36 days observed between the days 219 and 255 in Fig. 5(a) is attributable to the delay produced by long-lead components, which completely stopped the repair works for Option 1. The costs associated with repair works adds up to 1.163 million dollars for structural repairs and 1.141 million dollars for non-structural repairs, with a ratio of non-structural versus structural of 0.98.

For Buildings (3) and (4), in Figs. 6(a), and 7(a) respectively, it can be observed that since none of the structural components for both buildings have long-lead delays, the curves for structural components repairs are identical and are only shifted by the difference in the downtime due to delays. For non-structural components, the Option 2 for both buildings was not delayed for long-lead components, since the time required to finish structural repair works was longer than the time required for long-lead components to arrive at site (1 day). However, the longer time that was required for long-lead components to arrive at site for Option 1 (84 days) delayed the initiation of the repair works for Repair Sequence C for Building (3), and Repair Sequences C and E for Building (4). The repair costs for structural and non-structural components for both buildings were similar in this case. Additionally, the reason that explained the difference in total repair time for Option 1 between Buildings (3) and (4) can be observed in Figs. 6(a), and 7(a). In those figures, the time gap during which no repair work was performed (between days 182 and 255 for Building (3), and between days 191 and 255 for Building (4)) is longer for Building (3) than for Building (4). This observation reduced the difference in total repair times by 9 days, similar to the difference in total repair times between Options 1 and 2 for Buildings (3) and (4).

3.1.2. Occupancy measure of functionality

Considering the number of repair works per Repair Sequence, arbitrary occupancy level percentages were defined per Repair Sequences and Repair Classes. Additionally, the guidelines mentioned in the Downtime Assessment Methodology were used to define the repair

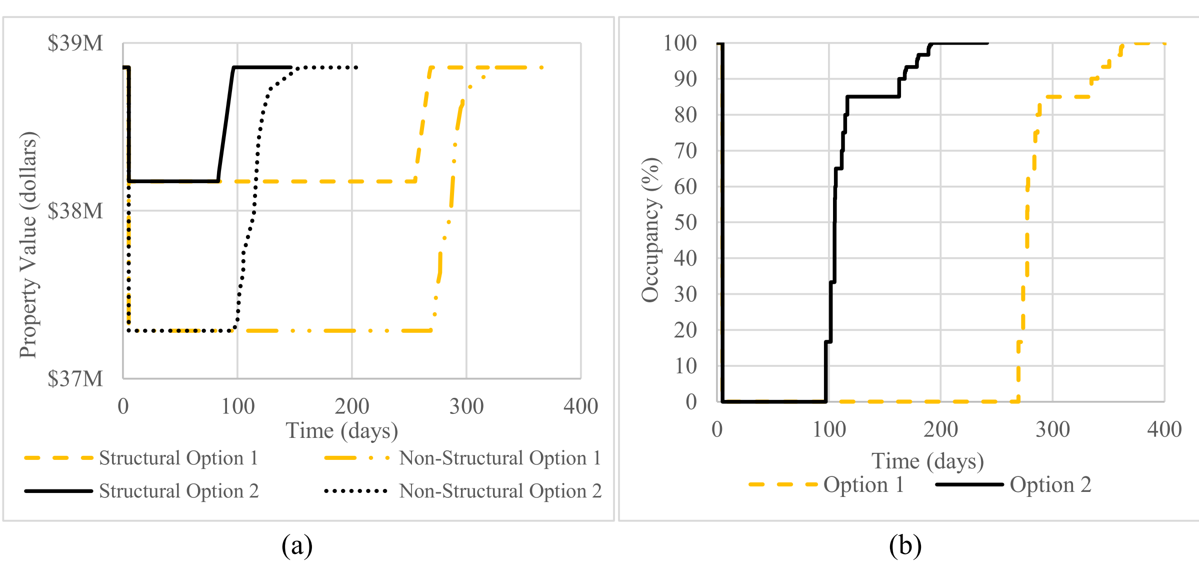

Fig. 4. Resilience Curves for Building (1) based on: (a) Repair Costs, and; (b) Occupancy Level for a Return Period of 475 years.

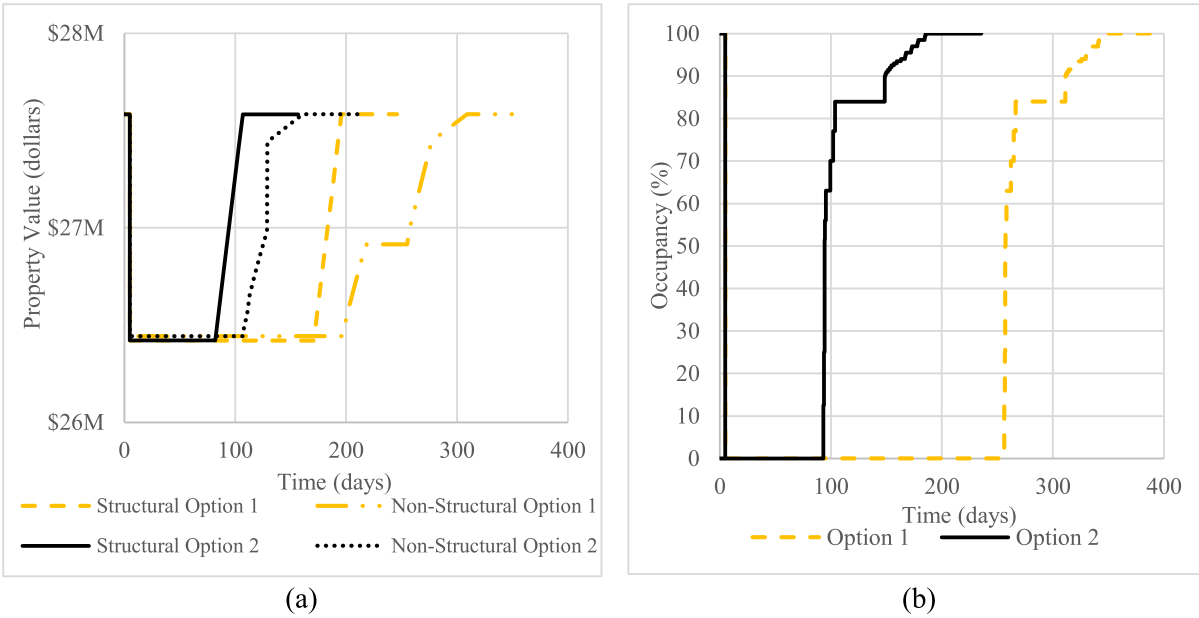

Fig. 5. Resilience Curves for Building (2) based on: (a) Repair Costs, and; (b) Occupancy Level for a Return Period of 475 years.

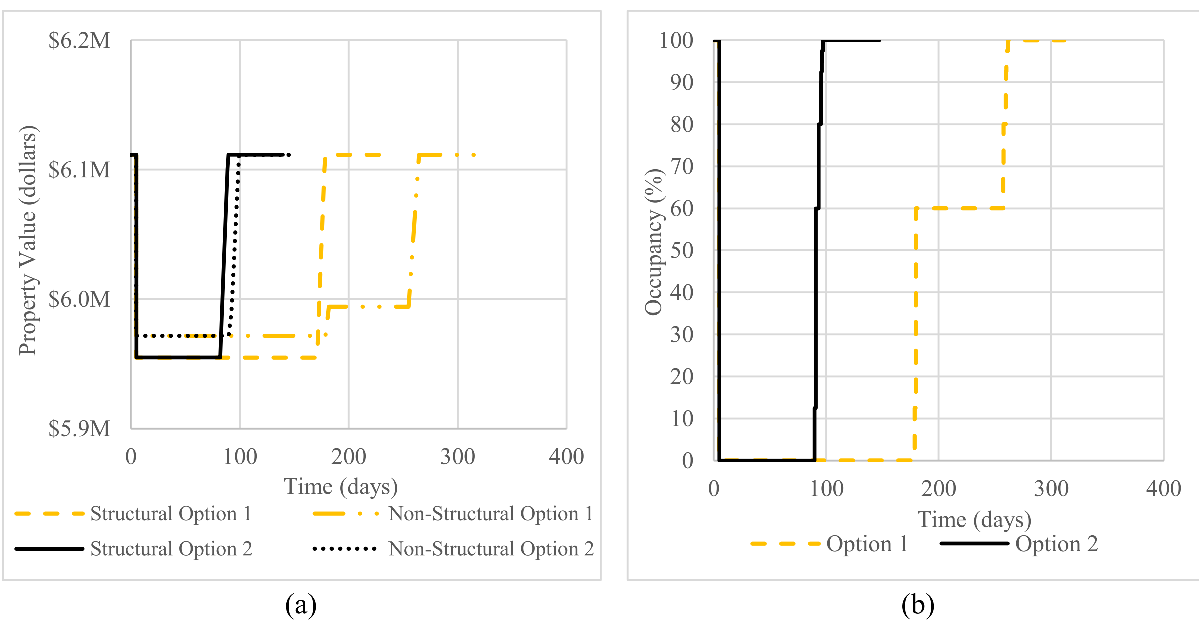

Fig. 6. Resilience Curves for Building (3) based on: (a) Repair Costs, and; (b) Occupancy Level for a Return Period of 475 years.

schedule. Thus, the resulting resilience curves developed on the functionality basis of occupancy were calculated and are shown in Figs. 4(b), 5(b), 6(b), and 7(b), for Buildings (1), (2), (3), and (4), respectively. For Building (1), both curves are again identical, as was observed before for the repair cost approach (Fig. 4(a)). However, for Building (2), a small difference can be noticed between the two options at the beginning of the repair schedule, but this difference rapidly disappears at the end of the Repair Class 3 (repair works essential to obtain re-occupancy state), when both repair schedules become completely identical. Again, the resilience curves for both Buildings (1) and (2) are only shifted by the delay imposed by the impeding factors.

For Buildings (3) and (4), a fast and early increase was observed in occupancy level percentages up to 60%. This observation is due to the fact that only some repair works for Repair Class 2 (repair works essential to obtain functional recovery state) required long-lead components, which means that all the repair works for Repair Class 3 (50% occupancy level) and some Repair Class 2 were completed without any delay. Also, for Building (3) Option 1, t_2 (refer to Fig. 3(b)) was relatively short compared to the same value for Option 2, which presented a higher value due to the long-lead components. The same observation was noticed for Building (4), but for this building, t_2 for Option 1 was longer than for Building (3).

3.2. *Resilience index as a function of earthquake intensity*

This section investigates how resilience indexes for the four example buildings vary as a function of S_a. The considered range for the S_a is 0.1 g to 2.0 g. The demand for each building, in terms of corrected drifts and accelerations per the FEMA P-58 procedures, was obtained for each S_a. As S_a increases, the resilience indexes are expected to decrease. It is also

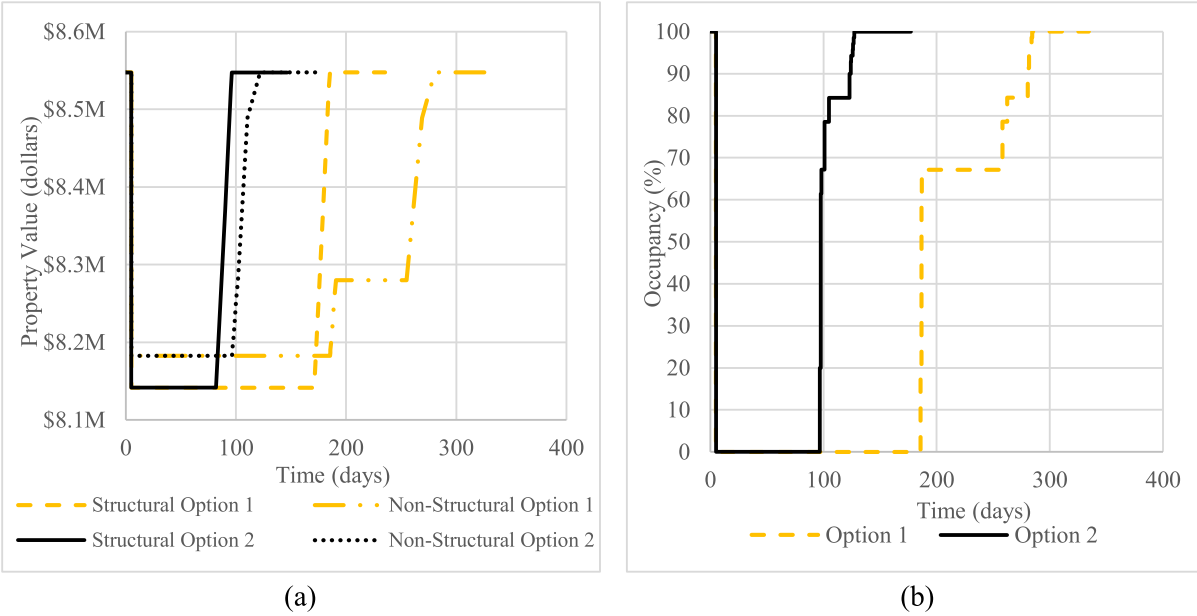

Fig. 7. Resilience Curves for Building (4) based on: (a) Repair Costs, and; (b) Occupancy Level for a Return Period of 475 years.

expected that buildings with shorter required repair times achieve higher resilience indexes. For a fair comparison of resilience indexes between the buildings, the reference time that is used to calculate the resilience index should be taken as the longest required repair time to achieve full re-occupancy between Options 1 and 2 for all the example buildings and for all the considered S_a values (which is 525 days for Building (1) Option 1 with an S_a of 2.0 g).

The first set of results for this analysis was obtained assuming that the collapse probability for the four example buildings was null. However, collapse occurrences are probable for the considered range of demand values. Thus, the results including the likelihood of collapse (out of 500 total realizations) are also presented for the considered range of S_a. Only one potential collapse mode, with complete failure in all floors in the building, was considered. Equation (1) was used to compute the resilience index including the collapse probability:

$$RI = \frac{RI_{NC}*(NR - CR)}{NR} \quad (1)$$

where RI is the resilience index that considers collapse probabilities, RI_{NC} is the resilience index for cases that did not collapse (out of 500 realizations here), NR is the number of realizations considered in the Building Performance Models (which is 500 for this case), and CR is the number of realizations that experienced collapse.

Fig. 8 presents the resilience indexes as a function of S_a for the repair cost approach for both Options 1 and 2 in Buildings (1), (2), (3), and (4) for the scenario that did not consider collapse probability. For S_a up to 0.8 g, Option 2 in Buildings (1) and (2) did not present considerable differences in the resilience indexes, but from this point onward, the decrease in the index for Building (2) was noticeably greater than that for Building (1), with the latter one ending up being the building with greater resilience indexes at high S_a values. It is important to note that at around S_a of 0.8 g, Building (2) presented higher repair cost than Building (1), and additionally, Building (2) had a lower estimated maximum possible repair cost. Consequently, the percentage that the repair costs represent from the estimated maximum possible repair cost

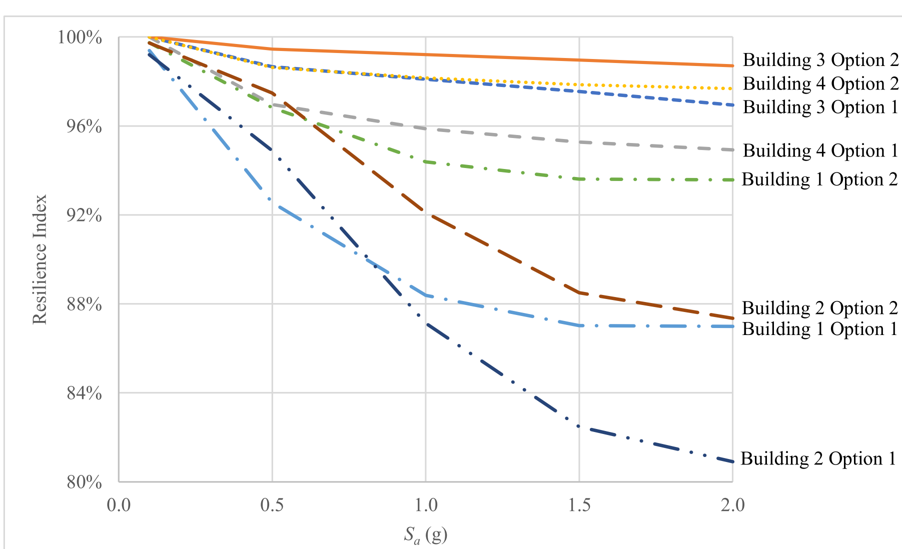

Fig. 8. Resilience Indexes (based on repair costs) per S_a for the Four Example Buildings Not Considering Collapse.

were higher for Building (2) than for Building (1), and this translated in the observed lower resilience indexes.

Option 1 presented better resilience indexes for Building (2) than for Building (1) for S_a less than 0.9 g. From this point onward, it was observed that, similarly to Option 2, the resilience index for Building (2) decreased faster than for Building (1), and again, this change occurred at the same S_a when Building (2) exceeded Building (1) in total repair costs. The fast decrease in the resilience index for Building (2) also resulted in Option 2 for this building to end-up with almost the same resilience index as Option 1 for Building (1). Additionally, for Building (1), it was observed that for S_a greater than 1.5 g, the resilience indexes only changed by 0.02% for Option 1 and 0.01% for Option 2, when for Building (2), the change was 1.10% for Option 1 and 0.80% for Option 2. This observation is reinforced by the fact that for the considered range of S_a, the required repair times did not change significantly above 1.5 g, and that the repair costs for Building (1) stayed constant while those for Building (2) continued increasing.

For Buildings (3) and (4), high resilience indexes were obtained, mainly because the repair costs for those buildings were not considerable. Low repair costs translated into low reductions in the functionality measure in this approach. Additionally, it can be observed that, as expected, the Option 2 for both buildings achieved higher resilience indexes than the Option 1.

Fig. 9 presents the resilience indexes as a function of S_a for the occupancy level approach obtained for the case that did not consider collapse probability for both Options 1 and 2 in Buildings (1) and (2). As will be presented later for the case that includes collapse probability, the change is more noticeable for S_a less than 1.0 g, which is due to the larger difference in required re-occupancy times for those scenarios than for S_a greater than 1.0 g, for which, the maximum required repair times were closer to the maximum value.

Fig. 10 presents the resilience indexes per S_a for the repair cost approach for both Options 1 and 2 in Buildings (1), (2), (3), and (4) considering collapse. There are not considerable differences between Option 2 for Buildings (1) and (2) for S_a between 0.1 g and 0.5 g. Option 1 for Building (1) has lower resilience index for S_a of less than 0.7 g when compared to Option 1 for Building (2), but the order switches at higher S_a values. This change occurred as Building (2) experienced collapse realizations at S_a of 0.7 g while Building (1) did not. Starting at S_a of 1.2 g, Building (1) started to have a higher probability of collapse than Building (2), explaining the faster rate of decrease in the resilience indexes. In general, Building (1) presented slightly higher resilience indexes than Building (2) for two reasons: the lower repair cost percentages, and the lower number of collapse realizations for the considered range of S_a. Moreover, the lower repair cost of Building (1) alone was sufficient to compensate for the detrimental higher repair times of Building (1) when compared to Building (2).

Buildings (3) and (4) experience a relatively large probability of collapse event even at small S_a values. For S_a greater than 1.0 g, neither Building (3) nor (4) have a resilience index higher than 20%, due to the high number of collapse realizations at those S_a. It can be observed that including the collapse realizations had a significant impact on the resilience indexes, especially for Buildings (3) and (4), which resulted in similar values for both Options 1 and 2. The resilience indexes of Fig. 8, which did not include collapse, remained above 80% for all considered buildings and scenarios, whereas Fig. 10 demonstrates that Buildings (3) and (4) were significantly affected even at small intensities.

Fig. 11 presents the resilience indexes as a function of S_a for the occupancy level approach obtained for the case that considered collapse probability. For Buildings (1) and (2), it can be observed that the change between Options 1 and 2 is more noticeable for S_a less than 1.0 g, which is due to the larger difference in the required re-occupancy times for those scenarios. At larger S_a values, the maximum required repair times were closer to the maximum value. For Buildings (3) and (4), as was observed for the repair cost approach, the resilience indexes are low for S_a greater than 1.0 g due to the large number of collapse realizations. However, as opposed to the repair cost approach, a clear difference between Options 1 and 2 for Buildings (3) and (4) can be observed. This is due to the larger difference in the resilience indexes between Options 1 and 2 for the scenarios that did not consider collapse probability. Additionally, both Options 1 and 2 for Building (3) presented higher resilience indexes than any of the options for Building (4), mainly due to the longer repair times required for this building.

4. Asset value approach

4.1. Theoretical concept and resilience curves for the four example buildings

This section presents a third approach to quantify resilience that uses asset value as the functionality measure. Asset value is defined by combining property value and property income. Property value is taken as the maximum repair cost, which maps to the cost to completely reconstruct the building, as discussed in Section 3.1. Each building was

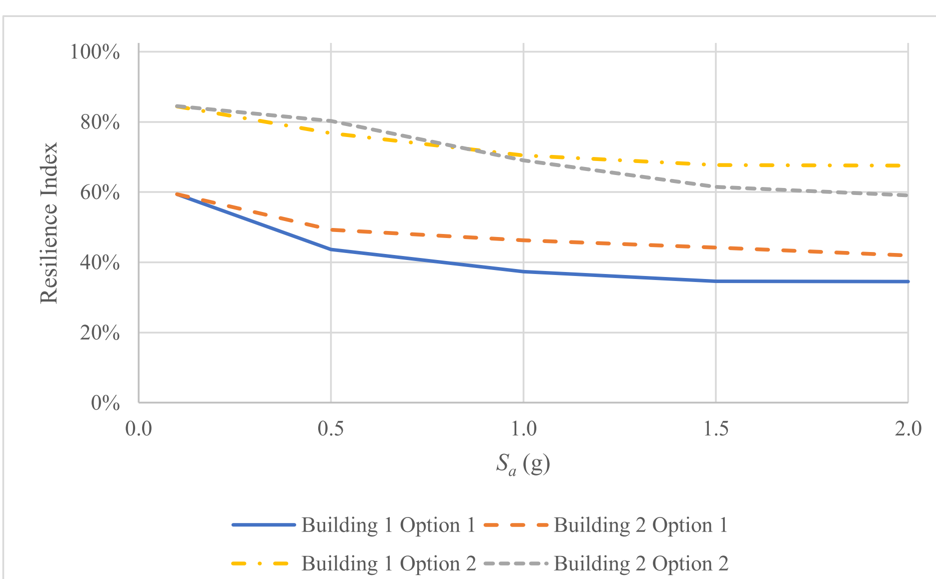

Fig. 9. Resilience Curves (based on occupancy level) per S_a for Buildings (1) and (2) Not Considering Collapse.

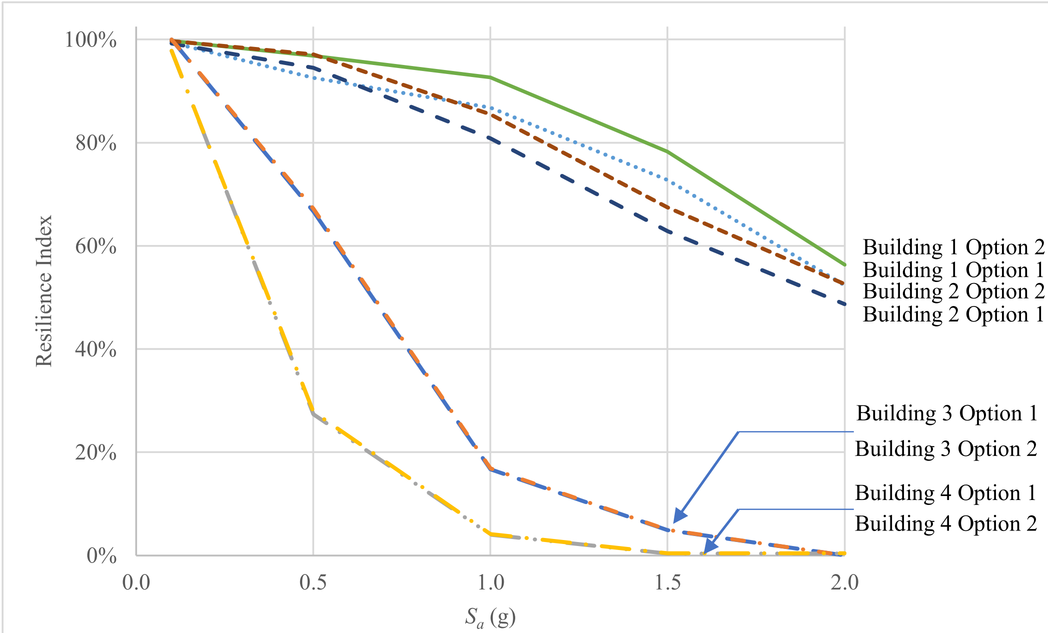

Fig. 10. Resilience Indexes (based on repair costs) per S_a Considering Collapse for the Four Example Buildings.

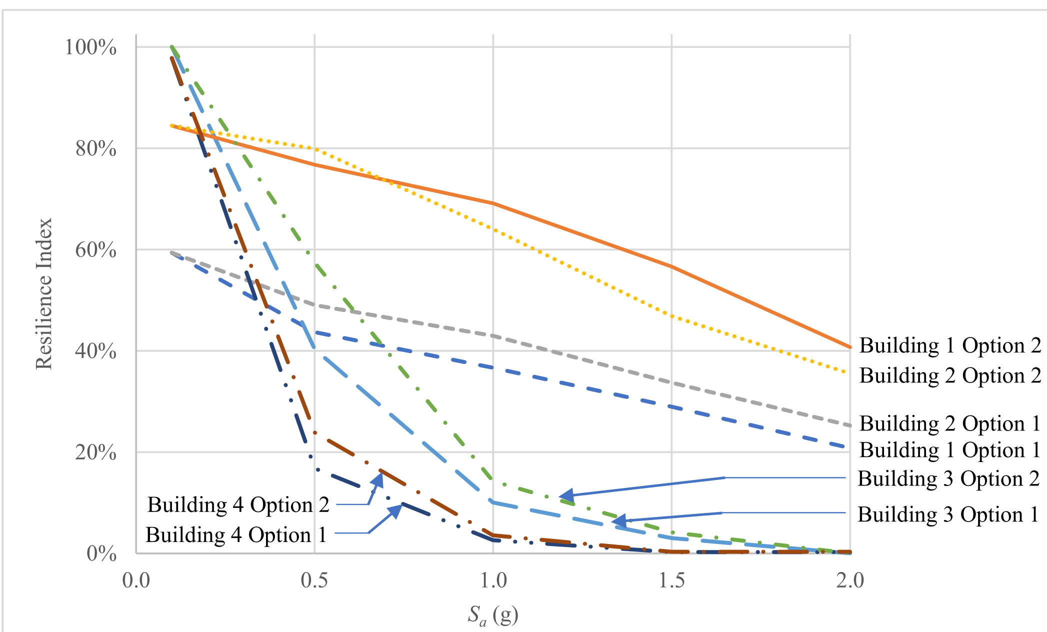

Fig. 11. Resilience Curves (based on occupancy level) per S_a Considering Collapse for the Four Example Buildings.

assigned an initial property value. As before, the occurrence of an earthquake results in damages that should be repaired, which is taken here as equivalent to a loss in the property value that will be progressively recovered. In other words, the repairs that are accomplished over time progressively return the property value to its initial value. However, in addition, property income is also considered here, taken as the difference between the gross income that the property generates by leasing the available space and the building's maintenance and operation costs (i.e., utilities, loan repayments, etc.). Here, the lease-income values were obtained from a real estate website [30] for the building location defined in Section 2.2. Additionally, the work presented below assumed that the losses in property income are constant over time but in proportion to the loss of occupancy. The considered scenario here assumes that in normal circumstances, the income and expenses break even and the property does not generate profit. As such, in a situation of reduced income, the property will lose money, which is referred from here on as losses.

Fig. 12 combines the concepts of property value and property income as explained above and illustrates how the asset value approach is implemented. Two different cases are presented. Case A, shown by the horizontal line in Fig. 12, corresponds to the "steady-state" when no earthquake occurs. There is no loss in the property value and the difference between income and expenses in the property income is null. Case B considers the occurrence of an earthquake, with a corresponding immediate drop in property value (down to Point A in Figs. 3(a) and 12). From this point onward, there is a downtime due to impeding factors

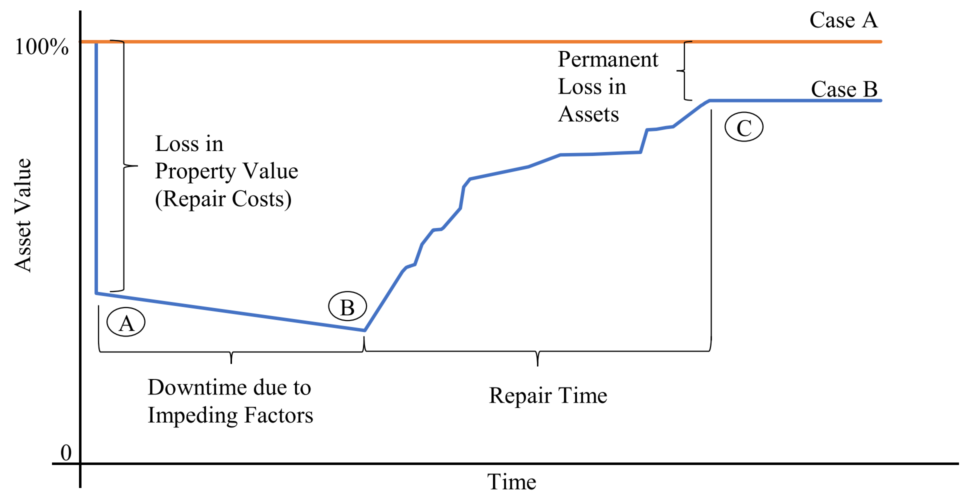

Fig. 12. Concept for Seismic Resilience based on Asset Values, Considering both Property Value and Property Income.

that prohibits the beginning of repair works. During this downtime, since repair works are not being performed, there is no recovery in the property value (lapse from Point A to Point B in Fig. 3(a)), and on top of that, there is no lease income collected. Assuming for simplicity that the property costs remain the same as before (i.e., loan repayments continue and utilities are needed for the repair crews to operate), then the property income produces a net loss. The rate of losses is the largest when the building is entirely unoccupied (shown by the downtime due to impeding factors, from Point A to Point B, in Fig. 12). Point B marks the beginning of the repair works on the building. From then onward, the repair works produce an increase in property value (i.e., from Point B to Point C in Fig. 3(a)). As the repair works concludes on certain floors for some Repair Classes, space progressively becomes available for leasing, translating into a progressive resumption of earnings from lease income. However, the rate of income recovered is less than that prior to the earthquake until the building is fully leased again. As such, there is still a net loss of property income from Point B to Point C, albeit at different rates as the building is progressively reoccupied. At Point C onward, the building returns to normal conditions (Case A in Fig. 12). However, as a consequence of the shortfall in lease income from Point A to Point C, a permanent loss in asset value has occurred. This is unlike the previous two approaches considered in Section 3 to quantify resilience, where the functionality measure used in those two cases returned the building back to its maximum value upon completion of repairs.

The repair times for both Options 1 and 2 for Buildings (1) and (2) are the same as for the occupancy level approach since the repair schedules are identical. Considering the above discussion and listed lease prices for the location, the resilience curves based on asset value were calculated for Buildings (1), (2), (3), and (4) for both Options 1 and 2, and are shown in Figs. 13, 14, 15, and 16, respectively. To provide a common reference time basis for the resilience calculations, the four curves are extended to the longest total repair time of all cases among the four example buildings (which is 359 days for Building (1) Option 1). As explained before, the resilience curves do not reach the initial functionality measure value (i.e., the initial property value in Fig. 12), because there is a permanent loss in assets in all cases. The permanent losses for each of the example buildings are reported in Table 3, both in absolute value and as a percentage of the initial property value.

Points A, B, and C in Fig. 12 can also be tracked in Figs. 13, 14, 15, and 16. For Building (1), the initial property value dropped to $36.61 million at Point A for both Options 1 and 2 (the total repair cost for Building (1) is $2.25 million). Downtime due to impeding factors for Option 1 took 251 days and the asset value dropped to $35.49 million at

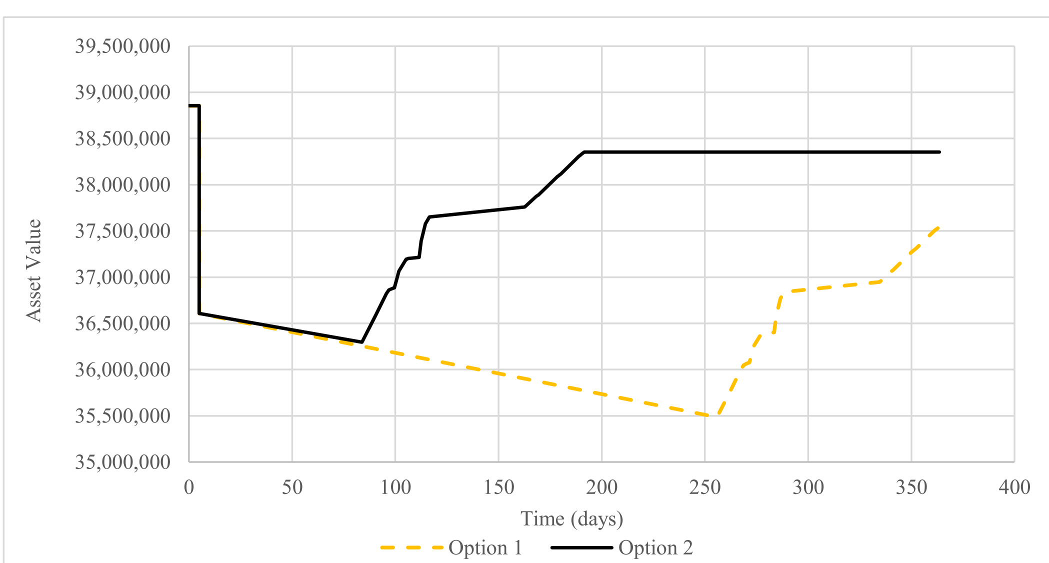

Fig. 13. Resilience Curves (based on asset values) for Building (1) for a Return Period of 475 years.

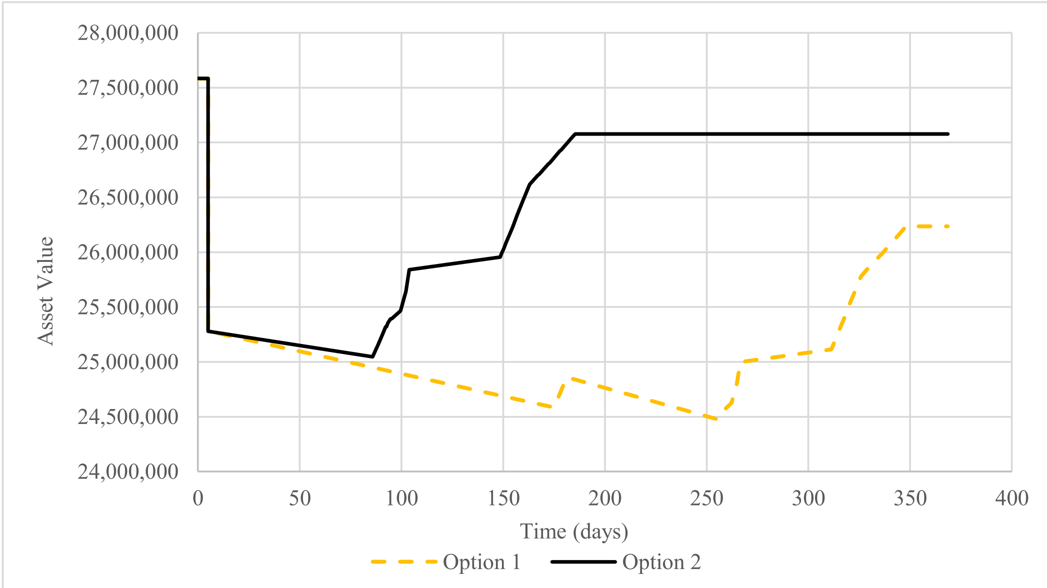

Fig. 14. Resilience Curves (based on asset values) for Building (2) for a Return Period of 475 years.

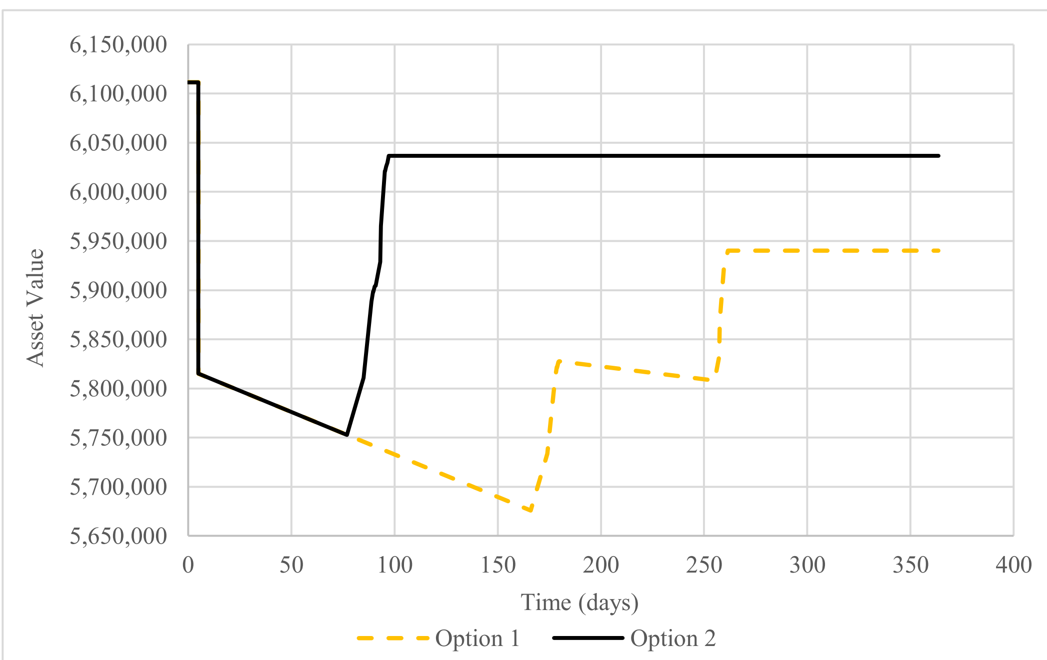

Fig. 15. Resilience Curves (based on asset values) for Building (3) for a Return Period of 475 years.

Point B, which is an additional $1.12 million drop with respect to Point A. The repair works for Option 1 concluded 359 days after the occurrence of the seismic event, with an additional property value loss of $190,000 dollars from Point B to Point C, resulting in an asset value of $37.54 million after repairs. For Option 2, Point B is 79 days after point A, with a drop of $311,000 in asset value. At point C, 187 days after point A and an additional $190,000 in property value loss, the final recovered asset value is $38.35 million. Note that the repair schedules for Options 1 and 2 are identical after the downtime due to impeding factors, as was observed in previous sections for the repair cost and the occupancy level approaches. A similar curve was obtained for Building (2), following similar trends, except that continued decrease in asset values is observed in the time lapse between days 181 and 255, which was due to the stoppage in repair works because of the long-lead components delay, as was explained before for Fig. 5(a).

Analyzing Buildings (3) and (4), Figs. 15 and 16 show the effect of the long-lead component in the repair schedule for Option 2 between days 180 and 255 for Building (3), and between days 187 and 255 for Building (4), respectively. Additionally, due to the longer downtime to begin repair works for Option 1, the permanent losses are greater for this option than for Option 2.

4.2. Resilience index as a function of earthquake intensity

For the occupancy level approach in Section 3.2, the resilience indexes were re-calculated based on the maximum required repair time

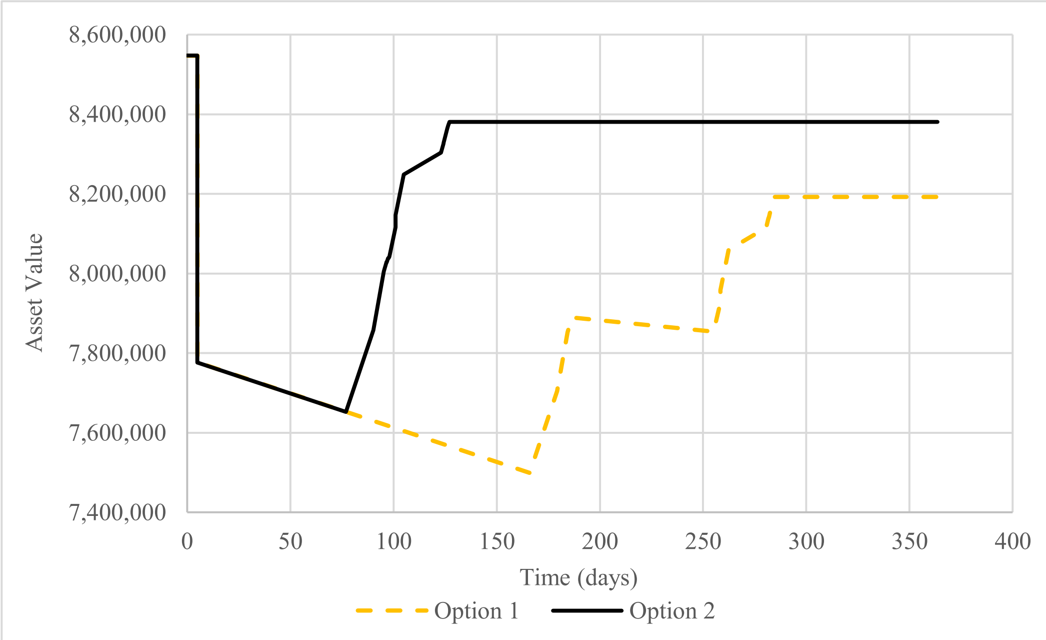

Fig. 16. Resilience Curves (based on asset values) for Building (4) for a Return Period of 475 years.

Table 3
Permanent Losses for the Four Example Buildings for a Return Period of 475 years.

Building	(1)	(2)	(3)	(4)
Option 1	$1,311,500.01	$1,347,828.47	$171,200.79	$355,095.25
Option 1 %	3.38%	4.89%	2.80%	4.15%
Option 2	$501,397.34	$507,053.34	$74,745.90	$166,396.54
Option 2 %	1.29%	1.84%	1.22%	1.95%

among all the S_a for both Options 1 and 2 and for the four example buildings, to adjust the reference time. Since the repair schedules for the occupancy level approach and the asset value approach are the same, a similar adjustment was made for the asset value approach. Fig. 17 presents the resilience indexes for the asset value approach considering the longest required repair time to achieve full re-occupancy for Options 1 and 2 for Buildings (1) and (2) and for all the considered S_a values (which is 525 days for Building (1) Option 1 for a S_a of 2.0 g) without

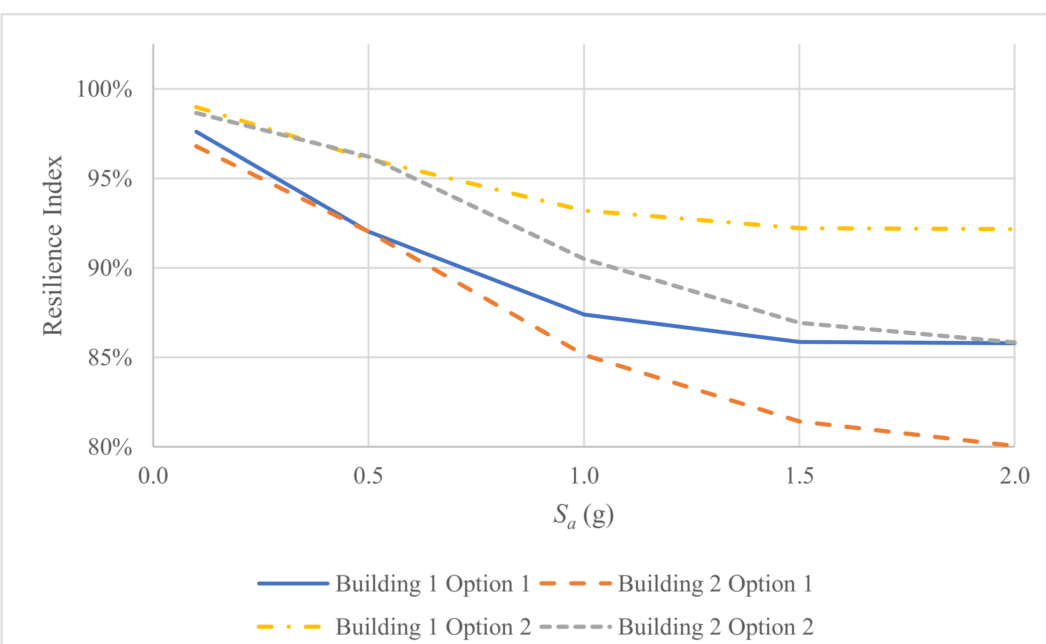

Fig. 17. Resilience Curves (based on asset values) per S_a for Buildings (1) and (2) Not Considering Collapse.

collapse consideration. Fig. 18 presents the results for the case with collapse, and including Buildings (3) and (4). Here, and different to what was observed for the occupancy level approach, no noticeable changes were observed when the longer required repair time was considered as the reference time. The similarities were due to the fact that, different to the occupancy level approach, the resilience indexes in this approach are more governed by the asset values, and more specifically, the repair costs, than by the repair times. Additionally, the repair cost percentages for Buildings (1) and (2) did not exceed 35%, and also the permanent losses for any S_a were below 6%. Therefore, the functionality measure in this approach can be reduced by 40% in the worst-case scenario, different than in the occupancy level approach, on which, 0% in the functionality measure (i.e., occupancy level) was obtained before the initiation of the repair works.

For Buildings (3) and (4), Fig. 18 show that the values obtained considering collapse probability for this approach compared to the results obtained for the repair cost approach were within 1.5% of each other. Therefore, the curves presented in Fig. 18 are analogous to the curves presented in Fig. 10. This observation can be explained by the fact that the square footage for Buildings (3) and (4) (which is relatively small compared to the square footage for Buildings (1) and (2), refer to Table 1) translated into small property incomes (and losses), and thus had a minimal effect on the asset value as the functionality measure. The most considerable contribution to this functionality measure was the property value (i.e., repair costs), and hence, the results for this approach and the repair cost approach are similar.

Fig. 19 shows the resilience indexes for the four example buildings considering collapse and Option 2 for impeding factors, to provide a comparison between the three approaches presented in this work. It can be observed that for Buildings (1) and (2), there are small differences between the repair cost and asset value approaches due to the similarities in the functionality measure used for both approaches. The higher variations in the functionality measure for the occupancy level approach are translated in lower resilience indexes for the same two buildings. Buildings (1) and (2) have a lower probability of collapse when compared with Buildings (3) and (4). Given the high probability of collapse for Buildings (3) and (4), there are no noticeable differences between the repair cost and asset value approaches, and only small differences with the occupancy level approach.

The assumptions and mathematical formulation to quantify downtime and resilience indexes are consistent for the four buildings and three functionality measures. Thus, the comparison of results between cases is valid, noting that the focus is not on the absolute resilience index of a given building. In other words, what matters here is not the absolute value of any given resilience index, but the contrasting magnitudes when resilience is calculated using different functionality and how it meets (or not) relative engineering expectations of the possible magnitude of what would be a meaningful resilience quantity given various damage scenarios.

5. Conclusion

In the perspective of some quantification frameworks, resilience largely dependent on two main parameters, namely functionality and time to recovery of that functionality lost at the time of the disaster. The work presented here compared the resilience indexes obtained for four different office buildings using three different proposed functionality measures, namely, repair cost, occupancy level, and asset value. This allowed to investigate how the choice of functionality measures considered to compute resilience, together with the time required for repairs, influenced the resilience indexes obtained for each building.

Parameters related to financial conditions, contractors, and component availabilities were assumed to determine the impeding factors following the procedures of the Downtime Assessment Methodology from REDi. For the repair cost and occupancy level approaches, it was considered that the functionality measure is recovered completely after the completion of repair works. Occupancy levels for different Repair Classes were assumed considering the level of completed repair. To the best of the authors knowledge, there is no literature on the topic, and it is acknowledged that mapping of the occupancy levels to Repair Classes should be further investigated to verify or improve the assumptions. For the asset value approach, it was assumed that there is no profit during normal circumstances (i.e., income and expenses break even), and that the income is proportional to the occupancy level in the building. All these assumptions were consistent for the four example buildings to enable the comparison of the functionality measures and how the three

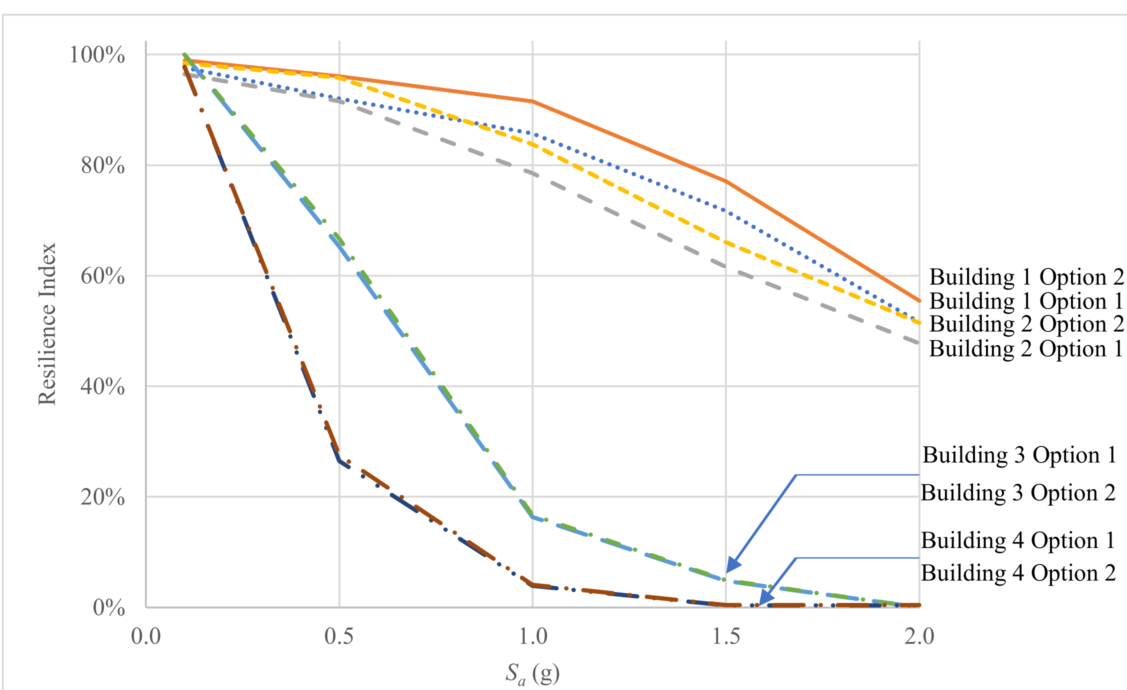

Fig. 18. Resilience Curves (based on asset values) per S_a Considering Collapse for Buildings (1), (2), (3), and (4).

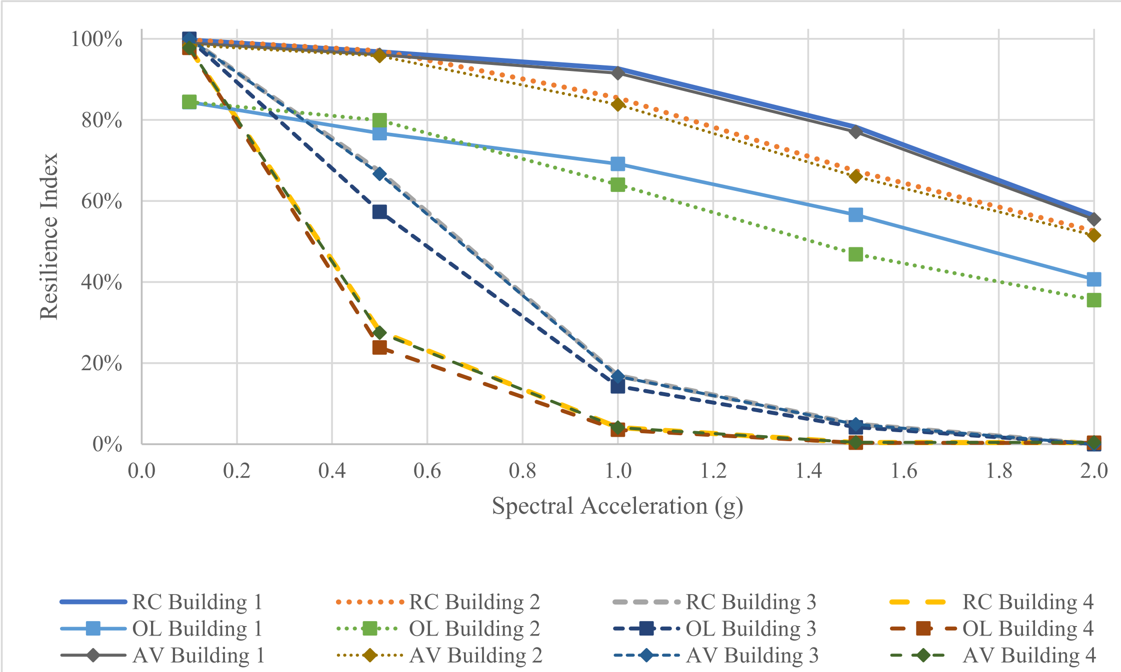

Fig. 19. Resilience Curves per S_a for the Four Example Buildings Considering Option 2 and Collapse.

approaches provide indicators of the resilience index of individual buildings.

Results showed that:

- For the occupancy level approach, the resilience indexes obtained were lower than in the repair cost and asset value approaches for the range of considered spectral accelerations. This was because for the occupancy level approach, the functionality drops to zero after the earthquake, contrary to the other two approaches where the functionality only drops by a certain percentage of the initial functionality, and in most of the cases remained considerably high. As such, it could be argued that the occupancy level approach is more representative of the actual functionality of a building, making the resilience index more meaningful.
- In spite of the above observation, there may be instances where repair costs and asset values as individual functionality measures can also be significant, possibly for other types of buildings with high value and low occupancy or buildings with different occupancies than commercial offices, such as industrial facilities on which higher demands (and therefore where higher damages to the building components, which can translate into higher massive repair costs) are expected to occur. This remains to be investigated in future research.
- For the asset value approach, lower resilience indexes were obtained than for the repair cost approach, because the asset value approach account for losses in income during the total building downtime (which includes the downtime due to delays and the required repair time). However, the similarities in the results indicates that these losses are not substantial compared to the repair costs, or property value in this case.
- It was found that, when computing resilience indexes, the collapse probability must be included in the calculations in order to obtain a realistic assessment. The resilience indexes obtained for the scenarios that did not consider collapse probability reflected a relatively high (and misleading) resilience for certain demands in some buildings (e.g., Buildings (3) and (4) at higher S_a).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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