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Evaluation of a strengthening approach for existing RC buildings in terms of resilience and cost efficiency

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Abstract. The aim of the present study is to assess the performance of a reinforced concrete (RC) building been retrofitted with a new precast insulated steel and concrete composite sandwich wall. The applied retrofitting method, as well as the selection of the performance level for design have been studied with reference to their impact on the retrofit cost and the estimated cost due to possible earthquake losses. As a case study an existing 8-story RC building has been selected that is strengthened with inverted-V steel bracings as well as with the application of the proposed insulated composite walls, respectively. By applying inelastic dynamic analyses with artificial accelerograms scaled to represent earthquake scenarios with specific probabilities of recurrence, the seismic response of the strengthened structure is defined for each scenario. The results of the aforementioned analyses are being correlated with the earthquake losses based on an established methodology. Eventually, the performance of each retrofit method is determined and then compared with the respective performance of the existing building. The most efficient method is defined by considering both the construction cost and the earthquake losses cost of each earthquake scenario.

1. Introduction

According to the Global Seismic Hazard Assessment Program (GSHAP map) on around 10% of the earth's land surface there is a 10% risk of occurrence in 50 years of heavy earthquake ground shaking and it is estimated that there may be about 600 million inhabitants in these zones [8],[20]. In addition, it is widely accepted that older buildings have been designed with outdated perceptions and do not comply with the modern standards in terms of earthquake safety.

The scope of the present paper is to propose an alternative method for strengthening existing RC buildings with the use of precast insulated composite sandwich wall elements and furthermore to compare this method to the well-established method of using inverted V chevron steel bracing as a retrofit method. The aforementioned comparison is performed using as a case study an existing 8-storey RC building in the city of Thessaloniki, Greece. The assessment of the retrofit method is conducted in accordance with the modern perceptions of the Performance Based Seismic Design

(PBSD). More specifically, the building that is used as a case study was strengthened with either of the compared methods so that it achieves the performance levels A1 and B1 of E.P.P.O. [4], hence four retrofitting scenarios were tested (2 retrofit methods x 2 performance levels). The assessment of those was made conducting nonlinear dynamic analyses with three artificial accelerograms which were scaled so that they represent earthquake scenarios with probabilities of exceedance 50%, 10% and 2% in 50 years for the seismic hazard level zone I of Greece. The results of each analysis and more specifically the inter-storey drifts were correlated to the damage level and to the monetary cost of the earthquake losses, according to established methodology of relevant literature [6], [11], [12]. Finally, for each retrofit scenario the construction cost is calculated and the cost of the earthquake losses of each earthquake scenario is considered in order to compare the performance of the two retrofit methods.

2. Retrofit Methods

The first retrofit method examined consists of an innovative precast insulated composite sandwich wall member (Figure 1a and Figure 1b). The examined insulated composite walls are consisted of two thin prefabricated external concrete layers of 50mm thickness reinforced with T188 steel grid of B500C steel category, as well as internally encased steel SHS50x5 profiles. The rest of the gap between the concrete sections is filled with an insulating material (such as Rockwool boards) of thickness equal to the height of the encased steel sections. The two external concrete panels are fully attached to the internal steel hollow sections. The composite behavior of the system is achieved with the use of U-shaped hoop shear connectors of 8mm diameter welded on the steel sections every 40mm (Ø8/40) while penetrating the concrete layers. For the application of the system, steel joints are implemented as vertical connectors at distinct points in the places where the RC existing members and the added composite system meet and additional steel anchored elements (in the specific case UNP sections) to the existing concrete columns are placed. Moreover, injections with concrete into the formed gaps (at the upper and lower end respectively) are implemented.

Figure 1a. Insulated composite wall specimen in 1:1 scale [5].

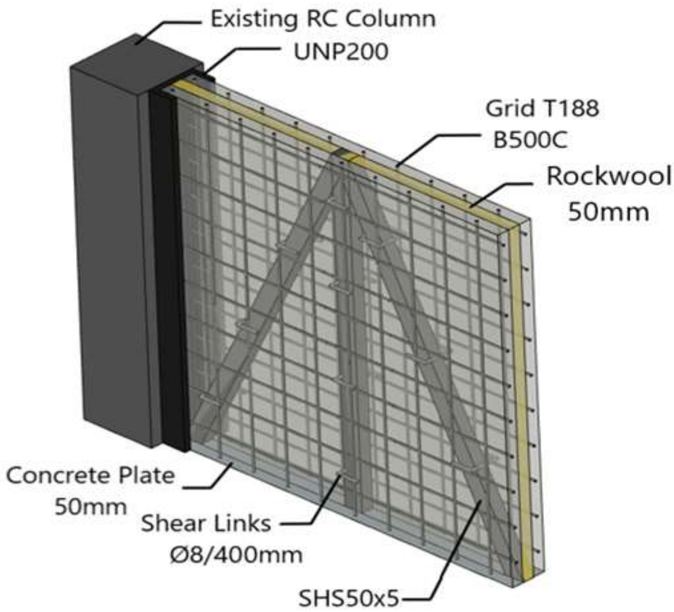

Figure 1b. Construction details of the insulated composite wall [14].

As a comparison to the insulated composite walls, the inverted V (Chevron) steel bracing method is selected. This choice was made due to the fact that it is usually an attractive option to the practitioners, since a concentric braced steel frame is a very efficient structural system because it requires relatively small amounts of materials to resist lateral forces [10]. Thus, it provides relative economy of their design and construction along with their sound strength-enhancing capacity and stiffness performance [18]. Their good seismic behavior combined with their cost efficiency have led to their frequent application in practice which rendered their inclusion in the case study appropriate.

3. Assessment methodology

The methodology for assessing the seismic performance of the existing building and each retrofit method is based on the comparison of the construction cost of each method as well as on the expected earthquake losses occurring from every case. The process of calculating the expected earthquake losses from an earthquake is often called 'loss assessment' in the relevant literature [17]. These methods are able to correlate the economic earthquake losses of building with quantities such as maximum inter-storey drifts and/or the maximum floor acceleration, or various damage indices proposed in the literature which are often obtained through inelastic dynamic analyses [2], [11], [12].

3.1. Analysis process

For the sake of assessing the response of the examined buildings (existing and retrofitted) quantities such as maximum inter-storey drifts had to be calculated. For this cause, nonlinear dynamic analyses with artificial accelerograms were carried out using the software SAP2000 v21.0.2. The artificial accelerograms (as shown in Figure 2) were developed by the Hellenic Institute of Engineering Seismology and Earthquake Engineering (ITSAK) and are considered representative of the seismic hazard of the earthquake zone which the building belongs to (Zone 1 of Greece with PGA 0.16g).

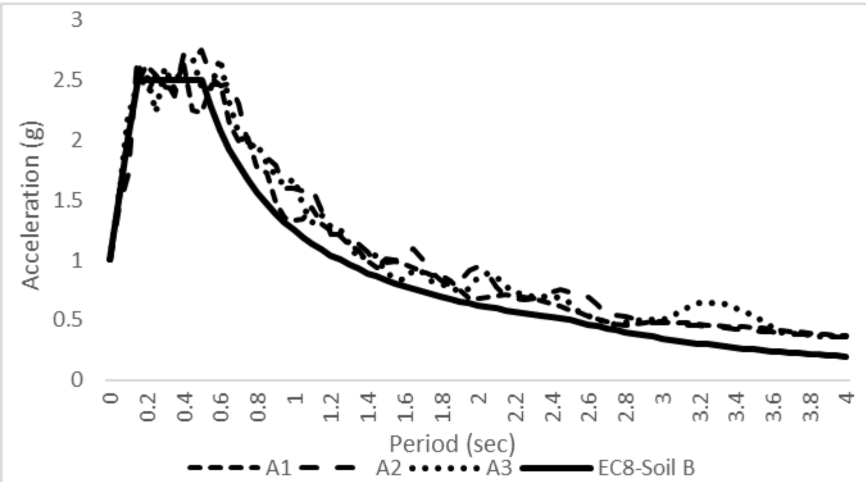

Figure 2. Acceleration response spectra of artificial accelerograms and design spectrum of the Eurocode 8 for Soil B scaled for PGA = 1 g and q = 1 (damping ratio 5%).

Each accelerogram was scaled, using well-established empirical formulae [16], in order to achieve Peak Ground Accelerations (PGAs) corresponding to probabilities of exceedance of 50%, 10%, and 2% in 50 years for seismic hazard level zone I of Greece. Hence, three seismic scenarios were examined (Table 1) for three artificial accelerograms for each of the five building cases.

Table 1: Peak Ground Acceleration of earthquake scenarios (seismic hazard level zone I).

Earthquake scenario (Probability of exceedance in 50 years)		
A	B	Γ
50%	10%	2%
0.10g	0.16g	0.25g

3.2. Seismic response and damage

Various quantities have been proposed in order to associate the seismic response of the structures with the induced damage such as maximum inter-storey drifts [11],[12], maximum floor acceleration [14],[21] or several other indexes. Maximum drifts are considered to be a proper measure for the damage level of structures as well as the most appropriate measure of the damage of the structural elements and the non-structural deformation sensitive elements of the buildings [1], [6]. Other quantities such as maximum floor accelerations, which are considered representative for the estimation of the loss of contents of the buildings, are not taken into account in the present study. This choice is common in literature [11], [12] since in most cases, naming residential buildings and office buildings, the repair cost of acceleration-sensitive non-structural elements is relatively small in comparison with the total cost of the earthquake losses (20% on average R/C building) [21].

More specifically, for the calculation of the damage due to each earthquake scenario the necessary maximum inter-storey drifts had to be extruded. Hence, the following steps were performed:

- The maximum inter-storey drifts Di of a great number of nodes i for each analysis case are obtained from the nonlinear dynamic analysis results.
- For each story j and for each direction (X or Y), the mean values of all elements' drifts DjX and DjY are calculated. When DjX or DjY exceeds the limit of 20‰, even for only one story, it is considered that the building has collapsed for the specific earthquake scenario. Thus, the next steps can be skipped.
- For each building k and for each direction (X or Y), the mean values of all stories' drifts DkX and DkY are calculated. From those values the maximum value Dkmax is determined.

The results of the above steps are being correlated with the damage of the building via Table 2 [6],[11],[12].

3.3. Economic analysis and earthquake losses

It is considered that earthquake losses in general can comprise the costs for repairing the damage of structural and non-structural components, loss of contents, rental and relocation costs, general income losses, injuries, and human fatalities. As it was mentioned previously, the cost of the loss of contents is considered to be as small amount of the total cost so it can be neglected. The same applies to the cost of income losses which can be considered significant only in commercial buildings. In addition, the cost of the relocation and the rental of the residents is omitted due to the lack of statistical data of previous (local) earthquakes that indicate the time the buildings remain out of service. Also, the implementation of data from other parts of the world is not so straightforward according to recent studies [19]. Finally, though methodologies which quantify the cost of injuries and human fatalities have been developed, they are neglected as quite ambiguous from a humanitarian point of view since these methodologies try to cost the value of human lives.

The cost of the post-earthquake repairs on the structural and non-structural elements is expressed as a percentage of the initial construction cost of the existing building and for the cases of the strengthened ones the cost of the retrofit is added to the initial construction cost. The correlation between the results of nonlinear dynamic analyses, the damage and the cost of the post-earthquake repairs is shown at Table 2 (for intermediate values, linear interpolation is conducted). The values of the table are taken from relevant literature [6],[11],[12]. Since the only criteria for estimating the earthquake losses is the cost of post-earthquake repairs and it is based on the values of Table 2, this can be considered as the fundamental assumption of the present study.

Table 2: Correlation between the inter-storey drifts, earthquake damage and the repair cost as a percentage of the initial construction cost.

Ductile wall and wall equivalent dual systems			
Performance Level	Damage State	Interstory Drift(‰)	Cost (% of Initial Cost)
1	None	Δ<0.67	0
2	Slight	0.67<Δ<1.33	0.5
3	Light	1.33<Δ<2.67	5
4	Moderate	2.67<Δ<6.67	20
5	Heavy	6.67<Δ<12	45
6	Major	12<Δ<20	80
7	Destroyed	20<Δ	100

The construction cost Cconstr of the existing building is being calculated in order to assess the cost of the earthquake losses, as it was above explained, as shown in Formula 6. Specifically, the cost of the concrete Cc and steel reinforcement Csr for the structural system of the existing building were calculated with current data according to the Greek public construction contracts [7] which includes not only the cost of the materials but also the cost of the labour work and the social security contributions (mandatory in Greece). In addition, the cost of the rest non-structural components Cnsc used as well as the cost of the construction works was assumed to be 700€/m2. The total cost of the structural system was normalized by the total area of the building and estimated at 54€/m2. Finally, the total construction cost of the initial building is calculated to be 754€/m2, a value in concurrence with relevant literature for the area of Greece [9],[11]. The cost was calculated with current market prices as the repair cost of earthquake losses is calculated with current prices.

$$C_{constr} = C_c + C_{sr} + C_{nsc} \quad (1)$$

Regarding the cost of each retrofit scenario (Civ and Ccw) the cost of the steel sections Css used was estimated based on whether the dimensions of their cross sections were over 160 mm or not [7]. Additionally, the cost of the demolition, dismantling and disposal of rubble Cdd, and the cost of installation Cinst of the new structural components was calculated to be 100€/m2 respectively (based on real cost data collected in Greece). Furthermore, the cost of fireproof coat Cfc was calculated for every steel section. The SHS sections inside the composite walls were excluded as they are protected from fire [12] and anti-corrosion coat Cacc was used instead.

Finally, concerning the insulated composite walls, the cost of the concrete plates Ccp and the cost of their steel reinforcement Csr were also calculated in accordance with the aforementioned method.

- $C_{iv} = C_{ss} + C_{dd} + C_{inst} + C_{fc}$ (2)
- $C_{cw} = C_{ss} + C_{dd} + C_{inst} + C_{fc} + C_{acc} + C_{cp} + C_{sr}$ (3)

After the quantification of the construction cost of the existing building as well as the cost of the proposed retrofits and the earthquake losses for each earthquake scenario, a methodology for comparing these results had to be implemented. Hence, in order to be able to assess the performance of each retrofit scenario considering their construction cost as well as the earthquake losses, a normalization to the maximum earthquake losses (Normalized Earthquake Losses or NEL) of each earthquake scenario was carried out. The fact that the maximum earthquake losses are used for comparing the results is due to the regulations of Eurocode 8 which states that whereas three accelerograms are used, the most unfavorable value of the response quantity among the analyses should be used [3]. More specifically, the maximum earthquake losses for each earthquake scenario were normalized to the construction cost of the existing building. In the cases of the strengthened buildings the cost of the retrofit was added to the calculated earthquake losses in contemplation of including the negative bias of the initial construction cost of each retrofit method to the final results.

4. Case Study

As a case study for implementing the aforementioned methodology an existing eight-floor RC building was selected which is located in the center of the city of Thessaloniki and had been constructed in 1966. For the enhancement of the seismic behavior of the building the two aforementioned strengthening techniques were applied with a view to satisfy the performance levels A1 and B1 of E.P.P.O. [4], respectively. Additionally, UNP200 sections were used to strengthen all the columns of the building due to the fact that they failed during the analysis of the structural model of the existing building. Furthermore, HE220A sections were placed underneath the cut-off columns to deteriorate the large deflections caused to the underlying beams. The foresaid interventions were used for both strengthening scenarios and, in every case, the structural steel used is S355 grade.

Regarding the case of the strengthening of the building with inverted V steel systems, SHS140x5 sections were used meeting at the center point on the upper horizontal member of the frame, reinforcing seven and four frames on every floor with a focus on accomplishing the performance levels A1 and B1 respectively. The frames were chosen with a view to improve the torsional behavior of the existing building.

In the case of the insulated composite walls; four and three frames were strengthened on every floor with composite walls of 15cm thickness satisfying the aimed performance levels. With a view to preserve the architecture of the existing building (and therefore provide a more realistic retrofit scenario), composite walls with openings for windows were used in the (visible) southwest side of the building; while in the southeast side solid composite walls with internal V shaped sections were used. In both cases SHS50x5 sections were used. Once more, the strengthened frames were chosen considering the improvement of the torsional behavior of the existing building.

Consequently, the calculation of the construction cost of the existing building was carried out as described in a previous section (referring to Section 3.3). The construction cost of the existing building as well as the cost of the retrofits are presented more analytically in Table 3.

Table 3: Construction cost of existing building and retrofit cost.

Cost of Existing Building	Retrofit Cost			
	A1		B1	
	Inverted V Bracing	Composite Walls	Inverted V Bracing	Composite Walls
933 685 €	162 584 €	120 849 €	133 230 €	115 186 €

5. Results

The existing building as well as the four retrofitting models were assessed using nonlinear dynamic analyses with three artificial accelerograms scaled to represent earthquake scenarios with probabilities of exceedance 50%, 10% and 2% in 50 years hence leading to the conduction of forty-five analyses. From each analysis the maximum displacement of the center of mass of the top floor and the inter-storey drifts where acquired. Afterwards, the damage levels of every model under the mentioned earthquake scenarios are determined and are afterwards are associated with cost of the earthquake losses using an established methodology of literature.

The maximum displacement of the center of mass of the top floor of each building was obtained conducting the analyses described in previous section (Section 3.2), for each accelerogram, for each earthquake scenario and for performance levels A1 and B1. The results were presented in two charts in Figures 3a and 3b respectively, according to the performance level, where the results were grouped in triplets of the three building cases (existing building, strengthened with inverted V bracings and strengthened with composite walls) in order to make the visual comparison easier. Moreover, the results were presented in increasing sequence starting from the earthquake scenario with probability of exceedance 50% in 50 years for the three accelerograms to the left and ending to the 2% in 50 years scenario to the right where it can be deduced that the minimum displacements occur in the 50% per 50 years for accelerogram A1 while the maximum displacements occur in the 2% per 50 years for accelerogram A3 in both performance levels.

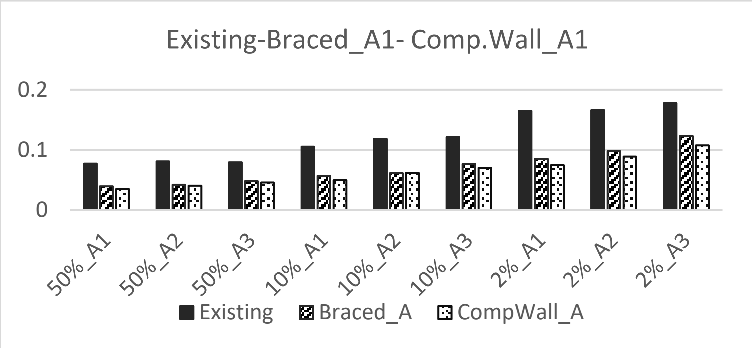

Figure 3a. Maximum displacement of the center of mass of the top floor of the existing building in comparison with the strengthened ones for performance level A1.

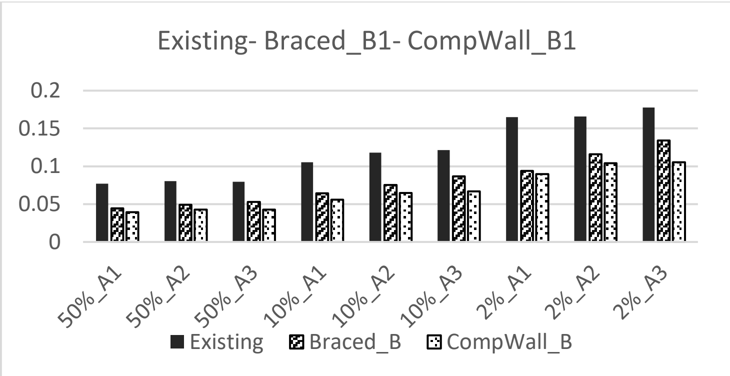

Figure 3b. Maximum displacement of the center of mass of the top floor of the existing building in comparison with the strengthened ones for performance level B1.

Besides the maximum displacements, the inter-storey drifts of every floor for each building case was extruded from the analyses as described in Section 3.2. Again, the inter-storey drifts are concerning each building case, each accelerogram, each earthquake scenario and each performance level. Not all of the 45 inter-storey drifts are shown for the sake of clarity. Instead for every building and for every earthquake scenario a mean value of the results of each accelerogram was calculated and is presented according to the performance level that is being accomplished. Figures 4a to 4fare concerning performance level A1 while Figures 5a to 5f are concerning performance level B1. It can be noticed from the diagrams that in every case and for both performance levels, maximum inter-storey drifts are observed in the case of the existing building as expected while in most cases the inter-storey drifts of the strengthened building with the insulated composite walls indicate the minimum values.

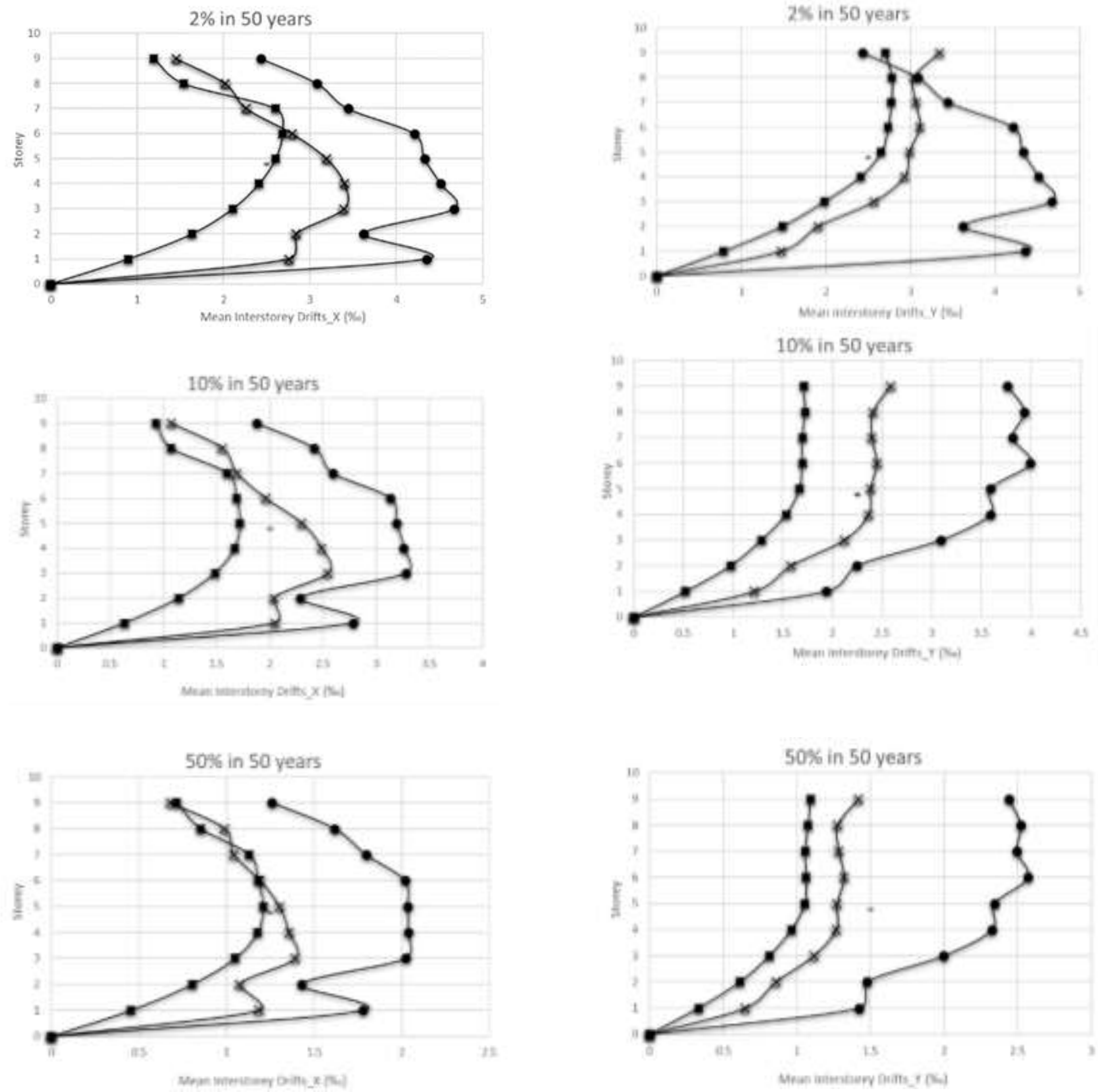

Figure 4a-4f. Interstorey drifts of each earthquake scenario with probability of exceedance 2%,10% and 5% in 50 years of the existing building in comparison with the strengthened ones for performance level A1 in X d in Y direction

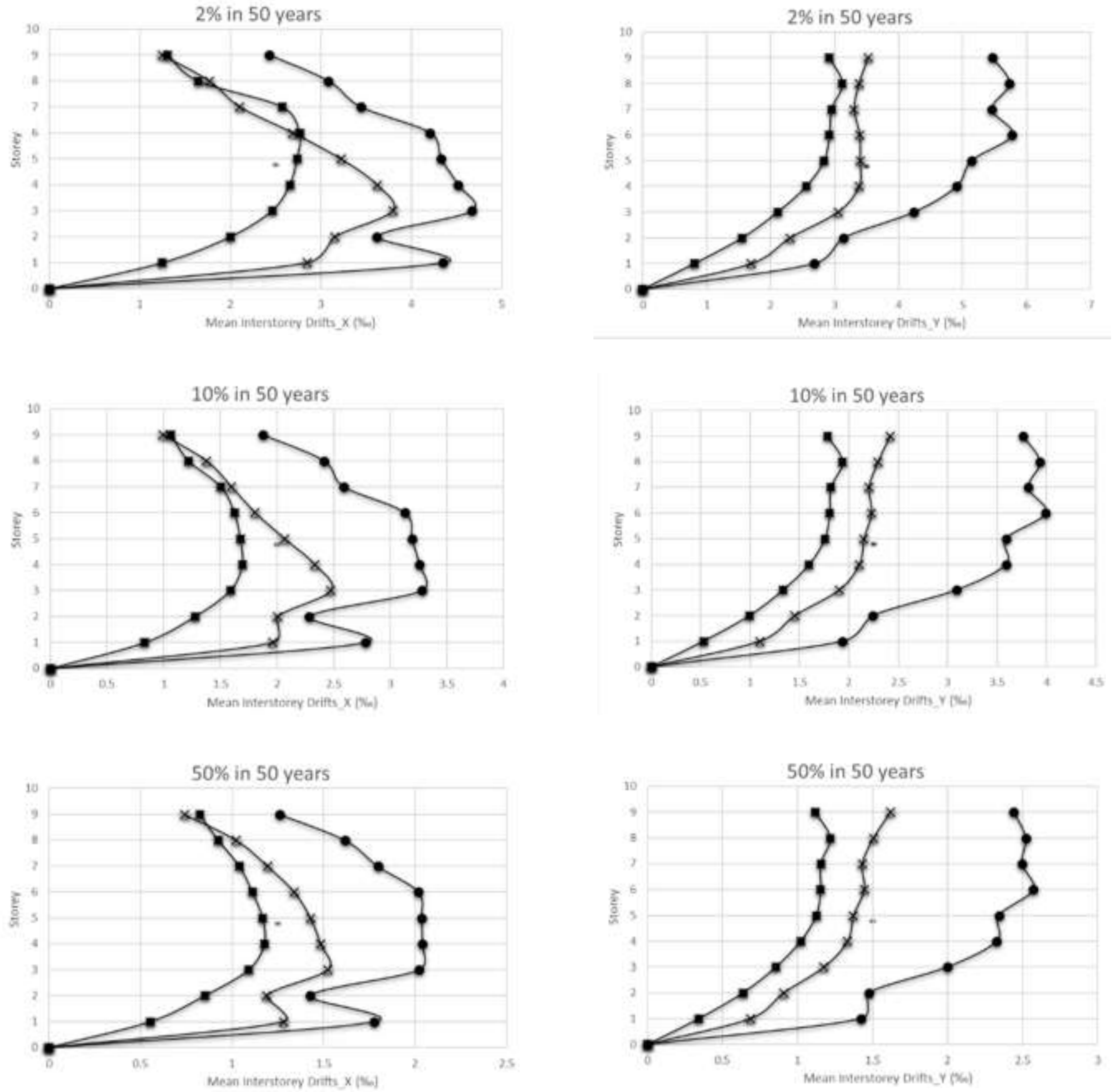

Figure 5a-5f. Inter-storey drifts of each earthquake scenario with probability of exceedance 2%,10% and 5% in 50 years of the existing building in comparison with the strengthened ones for performance level A1 in X and in Y direction

Figure 6 and Figure 7 present a diagram containing the comparison of the earthquake losses for each scenario in monetary terms for performance level A1 and B1 respectively.

Finally, Table 4 is presenting the monetary losses for each earthquake scenario, for the 3 accelerograms used and for the two performance levels. For the sake of the comparison of the losses, accounting also the construction cost, the Normalized Earthquake Losses index (NEL) is calculated, as described in Section 3.3. With 0 being the most cost-efficient case, meaning that no earthquake damage has occurred, and 1 being the worst, as it would mean that the building has collapsed. As the existing building indicates the highest NEL index, it can be deduced that the strengthening of the building is economically feasible. The insulated composite walls eventuate the most efficient choice as their indexes are lower compared to the inverted V bracings. Additionally, performance level A1 indicates lower indexes in every earthquake scenario, deeming the specific level the most satisfactory of the two compared levels.

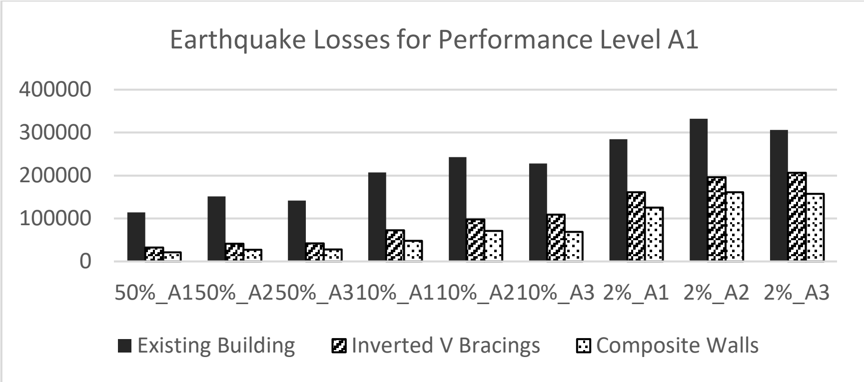

Figure 6. Comparison of the cost of the earthquake losses of the existing building with the strengthened ones for performance level A1.

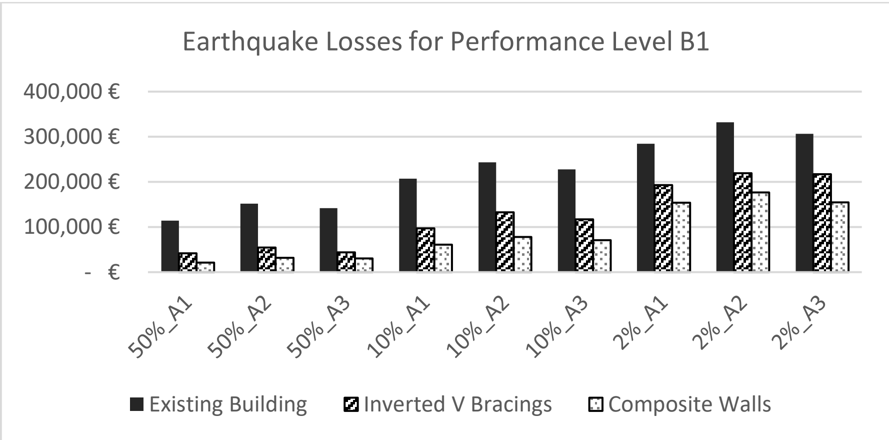

Figure7. Comparison of the cost of the earthquake losses of the existing building with the strengthened ones for performance level B1.

Table 4. Earthquake losses cost of strengthened buildings compared to the existing building.

Accelerogram	Earthquake Losses	Earthquake Losses for level A1		Earthquake Losses for level B1	
	Existing Building	Inverted V Bracings	Composite Walls	Inverted V Bracings	Composite Walls
50%_A1	114 160 €	32 214 €	21 068 €	41 620 €	21 542 €
50%_A2	151 573 €	41 413 €	27 058 €	54 576 €	32 039 €
50%_A3	141 894 €	41 720 €	28 227 €	44 087 €	30 498 €
N.E.L.	**0.162**	**0.038**	**0.027**	**0.051**	**0.030**
10%_A1	207 417 €	72 166 €	48 009 €	97 002 €	60 757 €
10%_A2	243 156 €	98 193 €	71 064 €	132 635 €	77 701 €
10%_A3	227 746 €	109 102 €	68 842 €	116 691 €	71 048 €
N.E.L.	**0.259**	**0.099**	**0.067**	**0.124**	**0.074**
2%_A1	284 747 €	161 057 €	125 515 €	192 836 €	153 914 €
2%_A2	332 055 €	195 997 €	161 310 €	219 042 €	176 955 €
2%_A3	306 568 €	206 420 €	157 496 €	216 911 €	154 438 €
N.E.L.	**0.354**	**0.188**	**0.152**	**0.205**	**0.168**

6. Conclusions and discussion

The objective of the present study is to evaluate an alternative method for strengthening RC buildings using insulated composite wall elements as well as to compare it to the well-established inverted V bracing retrofit method in terms of resilience (earthquake safety) and cost efficiency. For the sake of comparison nonlinear dynamic analyses of the existing building as well as to the retrofitting models were carried out using three artificial accelerograms scaled to represent earthquake scenarios with probabilities of exceedance 50%, 10% and 2% in 50 years. For every building case the maximum displacement of the center of the mass of the top floor and the inter-storey drifts were extruded where the latter got associated with the expected cost of earthquake losses. The two retrofit methods are assessed through their impact on the response of the building used as case study, but also through comparing the construction cost of each method and the expected cost of earthquake losses.

The results of the analyses showcased the following findings:

- The maximum displacement of the center of the mass of the top floor of the building decreased greatly with both strengthening methods while in the case of the composite wall system the decrease was greater. More specifically the mean value of the decrease of the specific displacement from every earthquake scenario compared to the strengthened building with inverted V steel braced frames for performance level A and B is 43.2% and 35.1% respectively while for the strengthened building with the insulated composite walls the mean decrease is 47.9% for performance level A and 44.7% for performance level B.
- Regarding the inter-storey drifts, for performance level A1 the decrease due to strengthening was on average 37.1% on X direction and 51.8% on Y direction while for performance level B1 the decrease due to strengthening was on average 31.5% on X direction and 39.0% on Y direction. Greater decrease is notice on Y direction for both retrofit methods while the insulated composite walls showcase equal or smaller inter-storey drifts with those of the inverted V bracings in every earthquake scenario.
- The cost of the earthquake losses of the strengthened buildings are on average 60% less compared to those of the existing building, while in the case of the retrofit with insulated composite walls the decrease is greater in every studied scenario.
- The normalization of the earthquake losses to the construction cost (NEL index) yields that the retrofit of the existing building is economically feasible while on the other hand that the insulated composite walls method with is more economically efficient in both performance levels examined. The insulated composite walls retrofit presented 71.5% decrease in the NEL index for performance level A1 and 68.4% decrease for performance level B1 with inverted V bracings indicted 61.8% and 68.4% decrease in the NEL index for performance levels A1 and B1 respectively.

The above results confirm that the insulated composite walls turn out to be the most preferable option not only due to their seismic performance but also due their low construction cost and to the expected earthquake losses in monetary terms. Based on the work presented, the insulated composite walls suggest a promising retrofit method which can be of interest for architects and engineers by dint of their seismic performance and cost efficiency. In addition, insulated composite walls can be sought out for contractors due to their quick in-situ installation which allows other trades to work in a comfortable environment whereas the composite walls are also suitable for manufacturers who are searching for new, viable product lines.

Conclusively, the fore-mentioned findings indicate the performance and the cost-effectiveness of the proposed method in comparison with a well-established retrofit method, this of the Chevron bracings without degrading the effectiveness of the latter. However, the generalization of those conclusions requires further experimental and analytical investigation to determine the effect of the proposed method with certainty in the response of the RC buildings.

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