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Seismic performance assessment of deficient RC structures retrofitted with different steel bracing systems

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Meriem Bouderradji
ORCID: https://orcid.org/0009-0006-0482-3508
LRHYA Laboratory, Department of Civil Engineering, University of Batna 2, Algeria
E-mail: m.bouderradji@univ-batna2.dz
Mohammed Salah Dimia
ORCID: https://orcid.org/0000-0002-1847-105X
LGC-ROI Laboratory, Department of Civil Engineering, University of Batna 2, Algeria
E-mail: ms.dimia@univ-batna2.dz
Soumia Gherabli
ORCID: https://orcid.org/0009-0001-8671-8974
LRHYA Laboratory, Department of Civil Engineering, University of Batna 2, Algeria
E-mail: s.gherabli@univ-batna2.dz
Ahmed Rafik Belakhdar
ORCID: https://orcid.org/0000-0003-4286-2349
Mining Laboratory, Civil Engineering Department, Larbi Tebessi University, 12002, Tebessa, Algeria
E-mail: ahmedrafik.belakhdar@univ-tebessa.dz
Noureddine Lahbari
ORCID: https://orcid.org/0000-0001-9468-0673
LRHYA Laboratory, Department of Civil Engineering, University of Batna 2, Algeria
E-mail: n.lahbari@univ-batna2.dz

Abstract

This paper discusses the use of concentric steel bracing systems as a global technique for retrofitting RC structures. A case study building with a five-story RC structure was retrofitted and tested using different types of bracing systems with different arrangements namely diagonal, X, and a combination between diagonal and X steel braces with tow arrangements. The main objective of the current study is to find out the most effective bracing system to upgrading the seismic behavior of deficient RC structures. The nonlinear static pushover and dynamic time-history analyses were carried out. The first method was applied by pushing the models until they arriving at a predefined target roof displacement. In the second method, a set of three natural earthquakes was employed to perform a dynamic time history analysis. The results indicate that the combined system of the diagonal and X braces using the second arrangement has the highest base shear and reaches the target roof displacement under pushover analysis. On the other hand, when using the response history analysis, it is the best system to reduce roof displacement compared to other techniques. However, steel braces cannot reduce the acceleration of the structure. The proposed combined system with the second arrangement is an effective retrofitting technique that has a much better seismic behavior and improves the ability to withstand even larger earthquake forces compared to other techniques.

Keywords: Retrofitting systems. Steel braces. Pushover analysis. Dynamic time history analysis.

Nomenclature

Rjb	Joyner-Boore distance
Rrup	Distance to the fault rupture plane

1. Introduction

Earthquakes present a risky situation for the vast majority of existing reinforced concrete buildings with sub-standard characteristics. Earthquake forces can extremely affect the structural performance of buildings by reducing their strength, capacity, stiffness, and stability. The inherent brittle behavior of concrete, insufficient transverse and longitudinal reinforcement details are among the significant frequent defects. Nevertheless, reinforced concrete structures can remain standing even after an earthquake. In a post-seismic performance assessment, it is necessary to decide whether to strengthen or reconstruct the deficient structure, considering the seismic forces for its service life. Many RC structures need to be retrofitted or strengthened in order to avoid the costs of demolition and rebuilding of new structures. Additionally, reconstruction imposes more costs than the financial aspects, such as disturbance to the residents and interruption of the functions of the structures, especially if there are very few hospitals or schools in remote regions. Most old buildings were not designed according to the newer seismic codes, in Algeria, the RC buildings built prior to 1980 have been extensively used framed systems to construct buildings even in high seismic prone zones. The existing substandard buildings perhaps are outnumbering the safe buildings. Therefore, these structurally deficient buildings should be seismically retrofitted to decrease their vulnerabilities via seismic events and to withstand seismic forces in compliance with current design norms. In light of recent knowledge regarding seismic motion and structural behavior, the need to assure satisfactory behavior under the seismic action of existing buildings according to poor seismic provisions has become an important task of the civil engineering community. The ambition of Performance-Based Earthquake Engineering is to offer a concept that consists of identifying several target performance levels that can be clearly arrived, or at the minimum not surpassed, when the structure is exposed to seismic excitation of a particular intensity level.

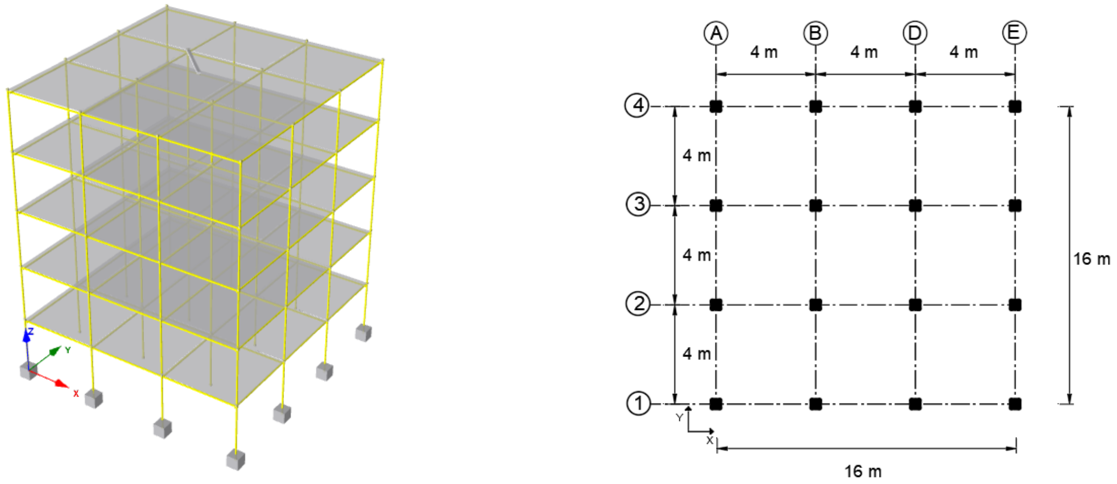
For seismic strengthening and retrofitting of reinforced concrete buildings, different techniques can be used, which can be divided into two major classifications: local and global. In the local retrofitting approach, several techniques can be employed, such as jacketing elements using reinforced concrete jacketing, steel strap adhesion, and reinforced polymer thin sheets, such as strengthened RC columns by covering them with carbon fiber-reinforced polymers (Ozcan *et al.*, 2008). However, in the global retrofitting approach, the structure has been retrofitted through the addition of new lateral resisting elements such as a shear wall (Canbay *et al.*, 2003), adding conventional steel braces (Fukuyama and Sugano, 2000), adding self-centering braces (Fan *et al.*, 2019), and utilizing supplemental damping and base-isolation (Durucan and Dicleli, 2010; Kassem *et al.*, 2020). Improving and upgrading deficient structures often enhances their strength, stiffness, ductility, or a combination of these. The addition of steel bracing systems is a highly successful method for seismic retrofitting of reinforced concrete buildings, it has many advantages for retrofitting techniques, such as increasing stiffness and rigidity and controlling the drift, which is necessary to reduce structural and non-structural damage caused by lateral loads such as seismic and wind loads. They also have the capacity to accommodate openings and have the minimum additional weight for the structure. (Thermou and Elnashai, 2006). In effect, the seismic loads absorbed by the additional bracing systems are immediately transmitted to the appropriate foundations created at their bases. Several bracing configurations have been extensively adopted for RC structures. However, bracing can also be applied to concentric or eccentric bracing. The concentric braces are connected directly to the beam-column joints and can be placed with different steel bracing types depending on the design, such as diagonal bracing, X bracing, V bracing, and chevron (inverted V) bracing. On the contrary, in eccentric steel bracing systems, each brace is connected eccentrically to a beam, the beam segment between the brace and the joint is called a link (Ahmad and Masoudi, 2020). Several specific numerical and empirical studies have investigated the behavior of steel braced RC structural systems against seismic loads, some of these studies are discussed in the following sections: a numerical work was carried out by Ghobarah and Abou Elfath (2001) which studied a 3 story RC structure repaired with eccentric steel bracing, the building performance was assessed the story drifts and damage indices. Maheri and Akbari (2003) investigated the behavior of knee-braced and X-braced RC structures using nonlinear pushover analysis, they concluded that the type of bracing systems possibly has a significant impact for the seismic behavior factor. Durucan and Dicleli (2010) in their research discussed the seismic reliability of a RC structure strengthened with D, V, and K forms of eccentric bracing systems through a fragility analysis. Godínez-Domínguez *et al.* (2012) discussed the seismic performance of regular RC frames with chevron braces. From the results obtained, they concluded that when using the chevron braces, the frames can achieve sufficient overall ductility capacity and obtain good over strength demand. Al-Dwaik and Armouti (2013) the authors compared the addition of eccentric steel bracing and RC jacketed columns as retrofit techniques for a five-story RC building, through nonlinear static and dynamic analyses, they found that the addition of eccentric brace to an existing RC structure was more successful in terms of improving efficiency the performance and lowering costs compared to RC jacketing for columns. Akbari *et al.* (2015) discussed the seismic fragility of reinforced concrete frames using two types of braces chevron and X. Their results demonstrate that retrofitting using internal steel bracing can minimize the damage with a considerable decrease when the chevron brace is adopted. Rahimi and Maheri (2020) examined the performance of strengthening an existing concrete frames using X steel braces, it was found that retrofitting with the addition of X steel bracing to an RC frame enhanced the global and local seismic behavior through nonlinear time history analyses. Beiraghi *et al.* (2022) studied the responses of a 2-story frame retrofitted with different types of bracing configurations including Λ, V, one-story X, two-story X and combined between Λ and V, braces. The results show that the frame performed better in terms of stiffness and strength when the two-story X configuration was used than the other types.

For assessing the seismic response of new or existing buildings, various analytical methods can be applied, including linear static and dynamic behaviour, nonlinear static (pushover analysis) and dynamic (response history) analyses. These methods have emerged as the most popular methods for design or seismic analysis, and can be employed for a variety of representations to the evaluated structure and its elements (Ghazal and Mwafy, 2022). The widespread pushover analysis is a practical and effective approach to represent the inelastic deformation with adequate accuracy (Hashemi Rezvani *et al.*, 2017), additionally, for their overall usability results, such as strength and stiffness of the building can be readily assessed (Saengyuan and Latcharote, 2022). Dynamic analysis can be used not only for the concept of new buildings but also for evaluating the behavior of existing buildings under seismic events. (Porcu *et al.*, 2019). However, it is very time-consuming and requires more computing effort than static analysis (Saengyuan and Latcharote, 2022). The validity of the assessment method relies on the properties of the structure and earthquake accelerations.

In this paper, the seismic performance of 5-story reinforced concrete buildings retrofitted with different steel bracing systems is studied. To reduce the seismic demands of the original structure, four cases of bracing systems with different arrangements were used: diagonal, X and a combination of diagonal and X steel braces with tow arrangements. This research aims to bring up scientific comparison analyses between the four cases of steel bracing systems to justify the adequacy of the chosen technique. Through, first, the static analysis shown in terms of pushover curves to estimate the lateral capacity. Then, a dynamic time history analysis was conducted to assess the dynamic performance in terms of roof displacement, roof acceleration, and maximum shear force.

2. Description of Structure Model

The structural system of the case study buildings in this paper was chosen to be reasonably basic and regular in plan and height to eliminate a different set of uncertainties from the analyses, as shown in Figure 1. The structure has plan dimensions of 12 m x 12 m, is considered with 3 bays in both X and Y directions, a span of 4.00 m for each bay, and consists of five floors, all floors have the same height of 3.00 m. All the columns have dimensions of 30 x 30 cm, their steel reinforcements equal 4ϕ14 at the corners and 4ϕ14 at the top-bottom and left-right sides. The main and secondary beams (X and Y directions) have dimensions of 30 x 35 cm, and their steel reinforcements were selected as 3ϕ12 at the lower and 3ϕ12 at the upper. All the detailed information about the properties of the structure members (dimensions and reinforcements) that were taken in the structural analysis are presented in Table 1 and illustrated in Figure 2. For all floors, live load is assumed equal to 1.5 kPa and dead load is considered equal to 5.23 kPa, and for the roof floors, live load is assumed 1.0 kPa and dead load is considered 6.48 kPa.



(a) **(b)**

Figure 1 - The selected building: (a) 3D view of structural model; (b) Floor plan.

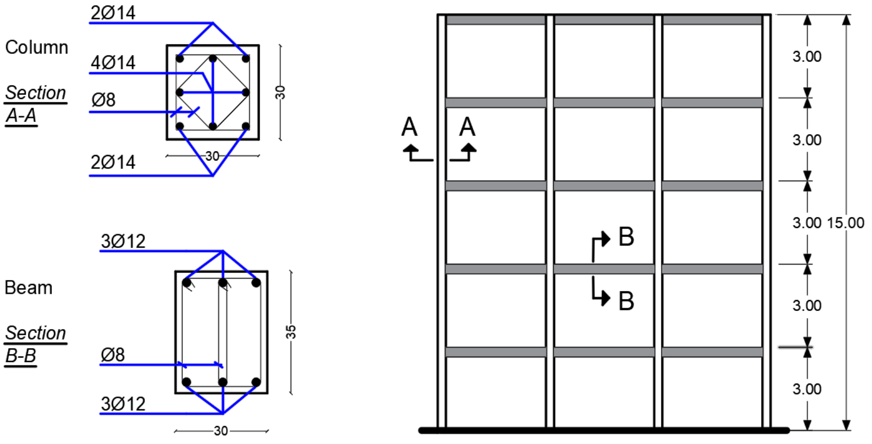


Figure 2 - Details of frame with cross-sections of elements.

Table 1 - The properties of columns and beams (dimensions and reinforcements).

Elements	Height / mm	Width / mm	Cover / mm	Longitudinal reinforcement	Transverse reinforcement
Columns	300	300	25	4 ϕ 14 and 4 ϕ14	ϕ8 / 150 mm
Main and secondary Beams	350	300	25	3ϕ12 at lower and 3ϕ12 upper	ϕ8 / 150 mm

3. Proposed Retrofitting Techniques

In this study, the results were discussed in detail by comparing the performance of the original RC building, with and without retrofitting measures. The retrofit structure models with different steel braces are divided into four cases, which are as follows:

i) The first case contains one braced bay in the middle using diagonal bracing (Diagonal model).

ii) The second case contains one braced bay in the middle using X-bracing (X model).

iii) The third case contains one braced bay in the middle using a combined bracing between diagonal and X braces, according to arrangement 1 (Combined Arr 1 model).

iv) The fourth case contains different braced bays using a combined bracing between diagonal and X braces, according to arrangement 2 (Combined Arr 2 model).

The added braces are located only on the exterior frames in the X and Y directions. The geometry of all four models is shown in Figure 3, and the cross sections of the brace models is shown in Table 2.

Table 2 - Cross section details of the braces.

Story number	Cross-section detail				Area (cm2)
	Case 1	Case 2	Case 3	Case 4	
	Diagonal brace	X brace	Combined brace arrangement 1	Combined brace arrangement 2	
1	W6x20	W6x20	W6x20	W6x20	37.90
2	W6x20	W6x20	W6x20	W6x20	37.90
3	W6x20	W6x20	W6x20	W6x20	37.90
4	W6x16	W6x16	W6x16	W6x16	30.60
5	W6x16	W6x16	W6x16	W6x16	30.60

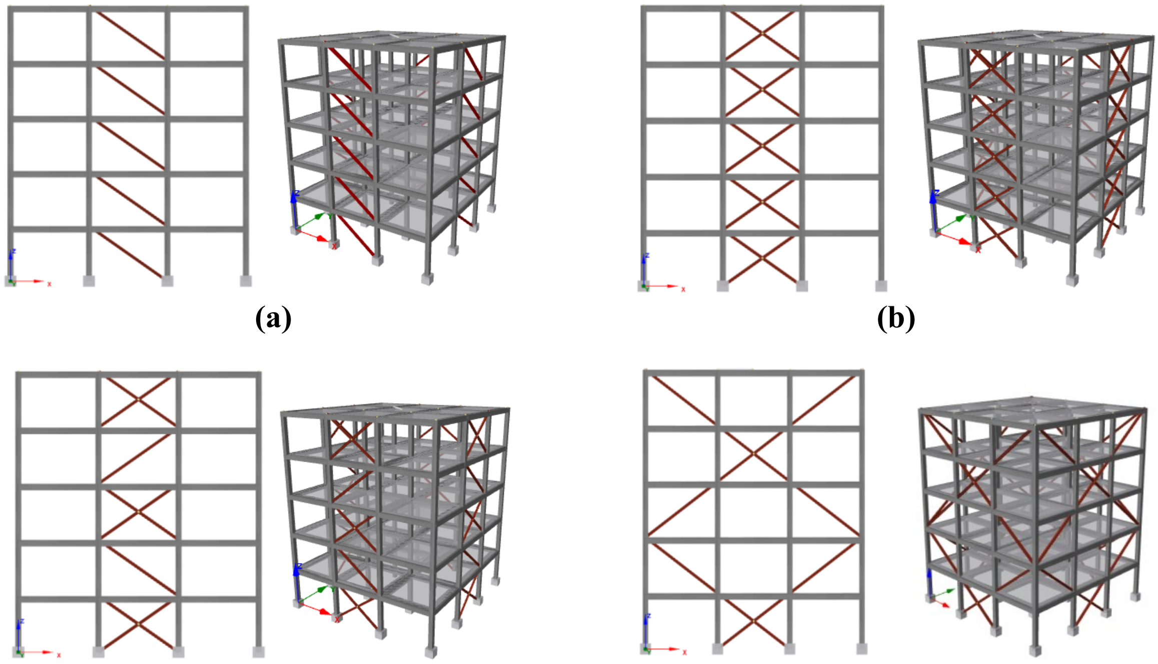
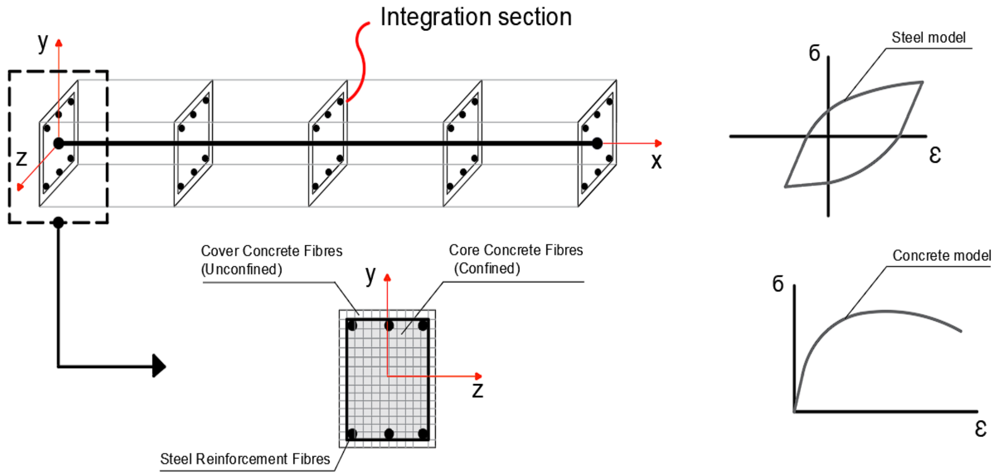

(a) (b) (c) (d)

Figure 3 - Elevation and 3D views of structures with different steel bracing systems: (a) Diagonal model; (b) X model; (c)Combined arrangement 1 model; (d) Combined arrangement 2 model.

4. Analytical Modeling Strategy

This section presents the numerical models, which were constructed using the finite element (FE) program SeismoStruct (SeismoStruct, 2022) with nonlinear modeling techniques to evaluate the seismic performance of the initial and retrofitted structures. This software can account for both geometric and material nonlinearity, and it was developed for predicting the behavior of several structure types. Furthermore, the SeismoStruct program uses the fiber-section approach for modeling. The structural elements beams and columns were performed as inelastic plastic-hinge force-based frame elements (infrmFBPH), the cross section of all members is divided into 150 fibers. The steel braces were modeled using the W cross section with truss inelastic elements. The slabs were modeled as rigid diaphragms. The software library includes a number of concrete and steel material models, that can be used in different ways. Throughout this study, for concrete, the nonlinear concrete model of Mander et al (Mander *et al.*, 1988) (con_ma) was applied. The modulus of elasticity was considered as 23500 MPa for the concrete material, the strain value related to the peak compressive stress of concrete was regarded as 0.002. And for both longitudinal, transverse reinforcements steel and braces elements the uniaxial Menegotto–Pinto steel model (Menegotto, 1973) (stl_mp) was selected as the constitutive model, while the strain hardening ratio was estimated to be 0.005 and the modulus elasticity was 200 GPa. The input models of the materials and fiber-section approach used in SeismoStruct are illustrated in Figure 4.



Figures 4 - Fiber-section approach and materials used.

5. Results and Discussions

5.1 Static Pushover Analysis

Pushover analysis is an effective approach for evaluating the existing structures, and can also be used to design new structures, that rely on redundancy or ductility to resist seismic forces (Mwafy and Elnashai, 2001). An analysis of static pushover has been done to evaluate the performance of the building when pushed to a monotonically increasing lateral displacement pattern and constant gravity load to get a certain target displacement. Their response is shown through the capacity curve, which is a scalar force-displacement relationship often expressed in terms of base shear versus roof displacement (Nour *et al.*, 2023). For this analysis, 3D pushover analysis was carried out to assess the seismic capacity of the original and four retrofitted models, under both uniform and triangular lateral load distributions. Due to symmetry and regularity in plan and height for the tested structure, only one direction for seismic action was examined (the x-direction).

The base shear-roof displacement relations obtained from the pushover analysis in the X direction for uniform and triangular loadings are presented in Figure 5. As clearly expected in the results, the peak base shear of the four retrofitted model's diagonal, X, combined arrangement 1 and combined arrangement 2 is 180%, 288%, 250% and 372% respectively, under uniform loading, and for triangular loading is 166%, 236%, 201% and 360% respectively, higher than the original model.

The results proved that the combination between diagonal and X braces with the proposed arrangement 2 increased the maximum base shear, elastic stiffness, ultimate strength, and ductility of the original structure higher than the diagonal and X braces. Regarding bracing configurations in cases with triangular and uniform lateral load distribution as shown in Figure 6. This figure indicates that the response structural of all models under uniform loading has a higher capacity when compared with triangular loading. Consequently, the triangular loading is the more critical distribution caused by more difficult seismic effects.

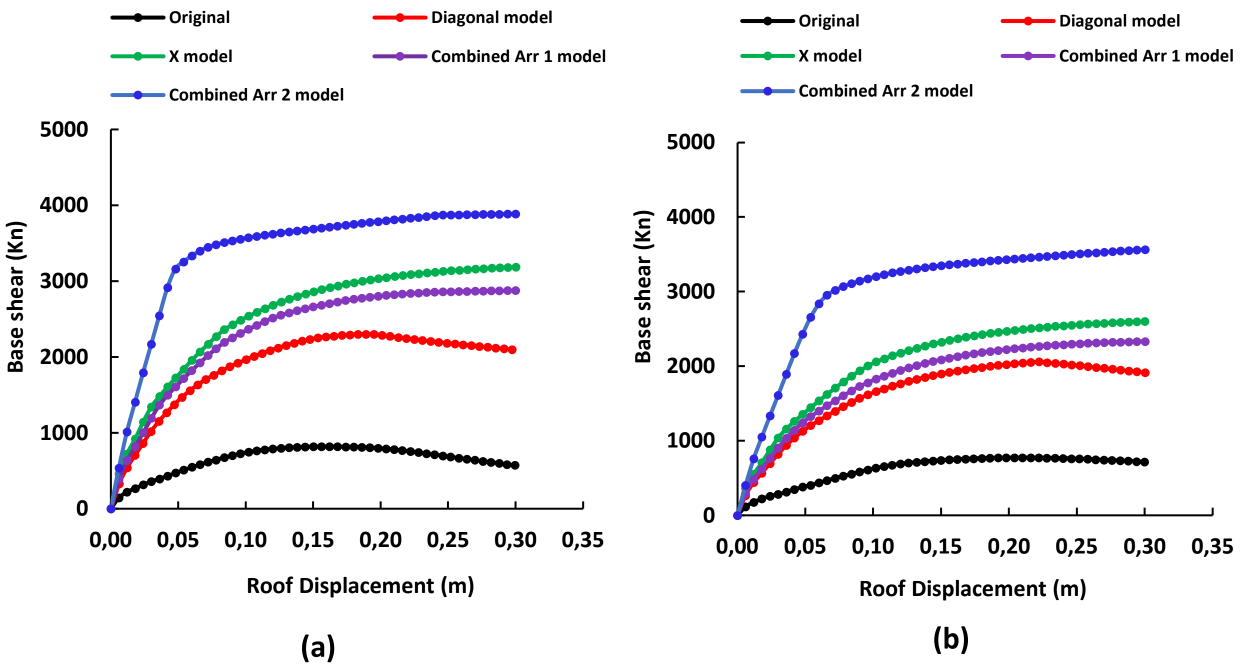


Figure 5 - The base shear-roof displacement relationships due to pushover loading: (a) uniform loading; (b) triangular loading.

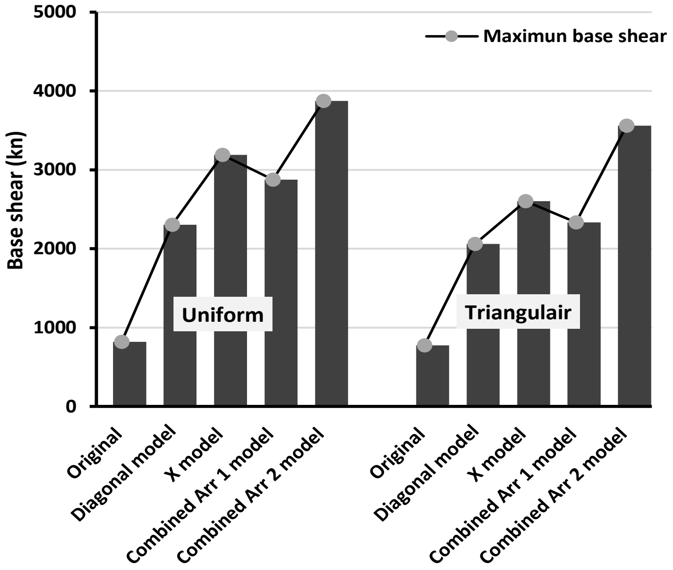


Figure 6 - Evolution of base shear in cases of triangular and uniform loadings.

5.2 Dynamic Time History Analysis

Dynamic time-history analysis is one of the most realistic and reliable analyses employed in the seismic performance evaluation of structures. Nevertheless, the accuracy of the results is dependent on the amount and characteristics of ground motion records such as duration, maximum value of acceleration, and frequency (Bourdim *et al.*, 2022). The acceleration time-histories are used as the applied dynamic loads. A suite of three near-fault and far-fault acceleration time histories has been chosen to estimate the nonlinear time history analysis. In this study were used Fruili Italy-01, Loma Prieta and Northridge-01 earthquakes, they were obtained from the PEER Center (Pacific Earthquake Engineering Research) NGA-West 2 database, their accelerograms are shown in Figure 7, and their characteristics are presented in the contents of Table 3.

Table 3 - Details of earthquake records.

Record	Year	Event	Station	Magnitude	Rjb / km	Rrup / km
1	1976	Friuli, Italy-01	Tolmezzo	6.5	14.97	15.82
2	1989	Loma Prieta	Salinas - John & Work	6.93	28.66	32.78
3	1994	Northridge-01	Mojave - Oak Creek Canyon	6.69	75.64	75.80

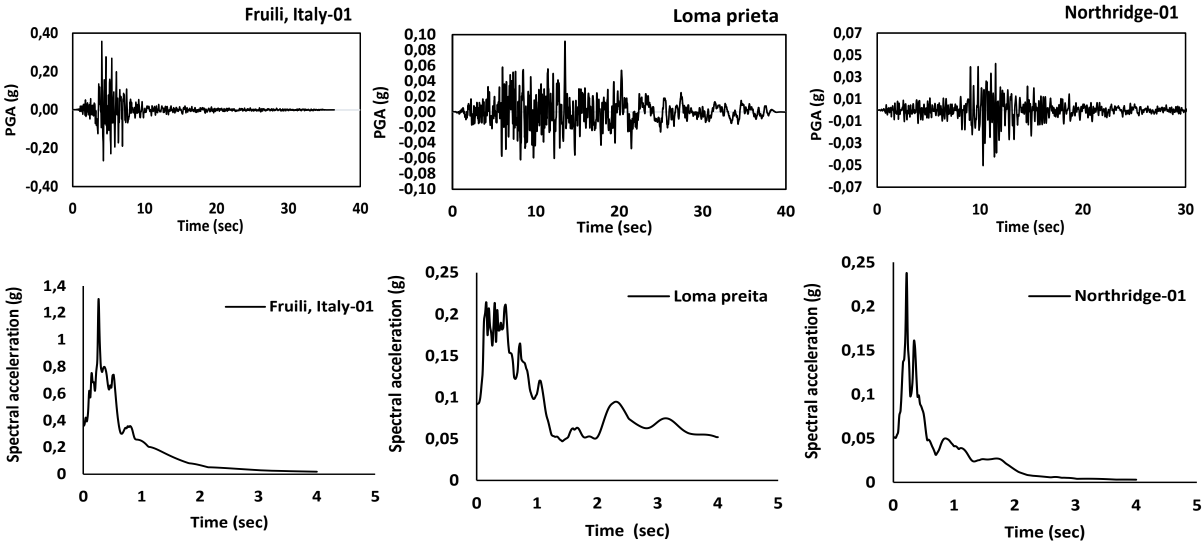


Figure 7 - Selected time histories from PEER.

Before utilizing the accelerograms in the nonlinear time history analysis, the three time histories were matched by using SeismoMatch with the design target spectrum. The method was done in two steps and was applied with a maximum of 30% tolerance, in the first step were matched to a period of 1 second, and then in the second step rematched with the same design target spectrum to a period of 4 second. The matched accelerations were used to carry out the time history analysis. Then they were applied at the base of all columns in the X direction. The related results of the dynamic time history analysis roof displacements, roof accelerations, and shear forces of the structures were obtained and compared to each other. Figure 8 shows the comparison of the graph of the design target spectrum with the mean response spectra developed for the selected matched records.

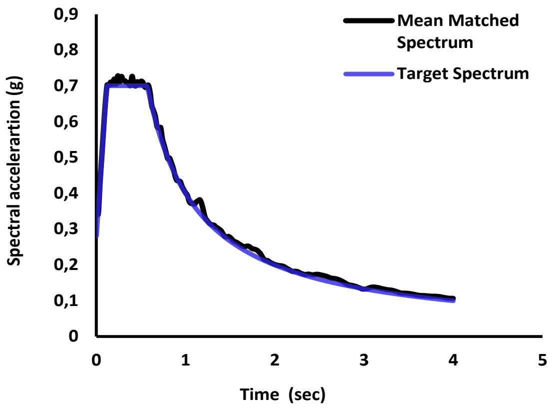


Figure 8 - Comparison of design and mean spectrum.

Comparison of roof displacement of all structures: Figure 9 outlines the time history of roof displacement response in the X direction of structures from nonlinear time history analysis under the Fruili Italy-01 earthquake.

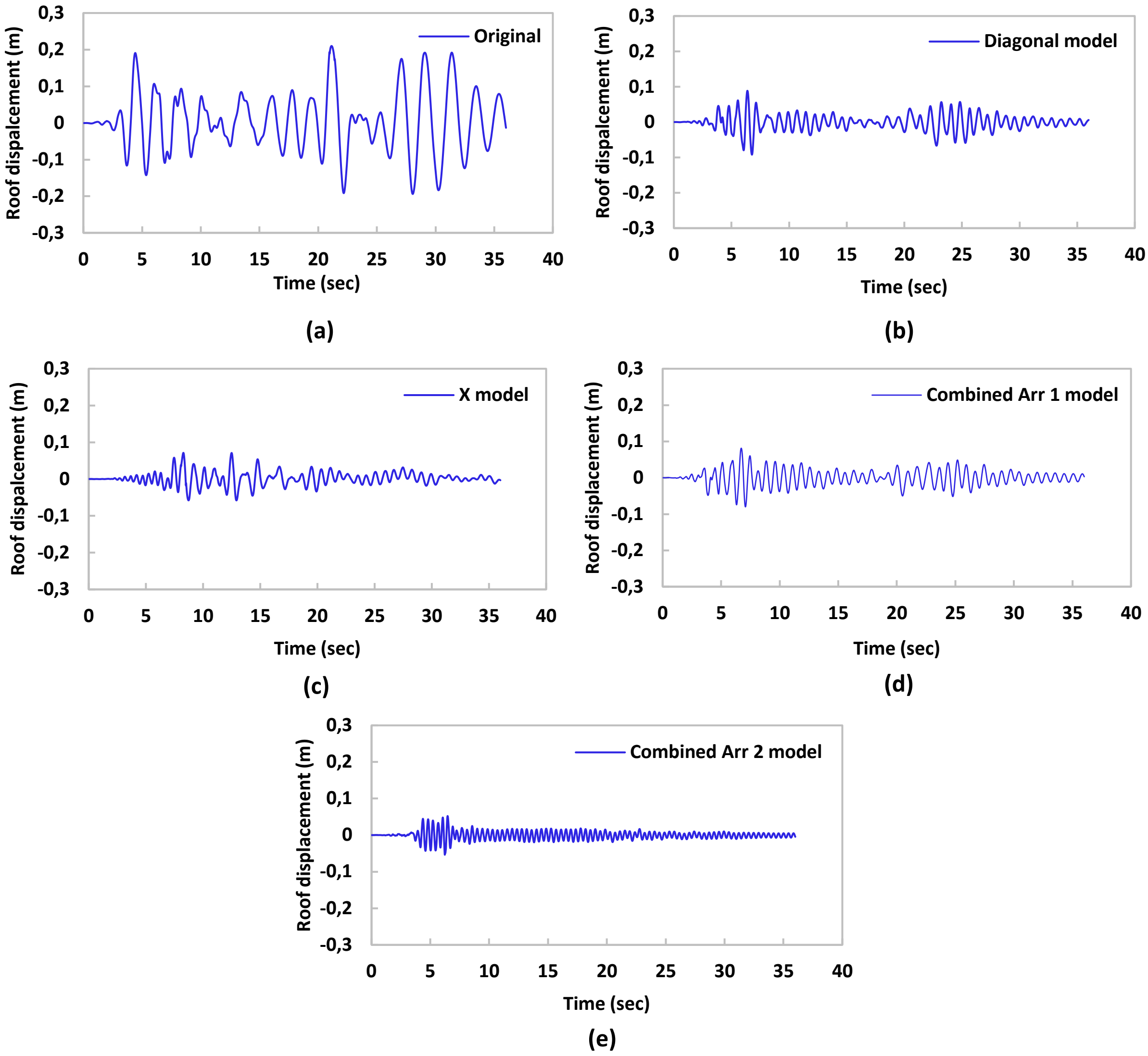
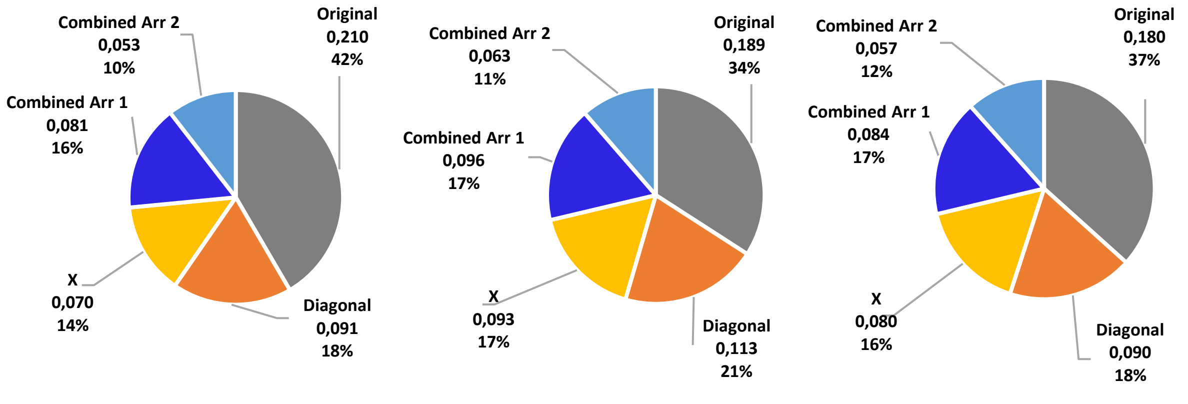


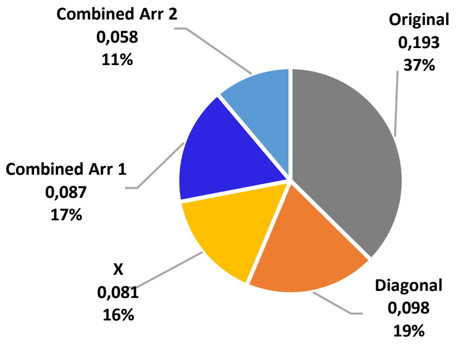
Figure 9 - Time-roof displacement diagram of all models under Fruili Italy-01 earthquake: (a) Original, (b) Diagonal, (c) X, (d) Combined arrangement 1, (e) Combined arrangement 2.

A comparison of the roof displacement values in the X direction for all models under the three selected records and their average were illustrated in Figure 10. As it is seen, the average roof displacement values of the diagonal, X, combined arrangement 1 and combined arrangement 2 models, exhibited a ratio about 50%, 41%, 45% and 29%, respectively, from the original model.

Based on the results, the roof displacement of the combined brace model combined arrangement 2 is much less than the other models. This remarkable reduction indicated that the combined brace model expressed less damage and thus more durability than the others.



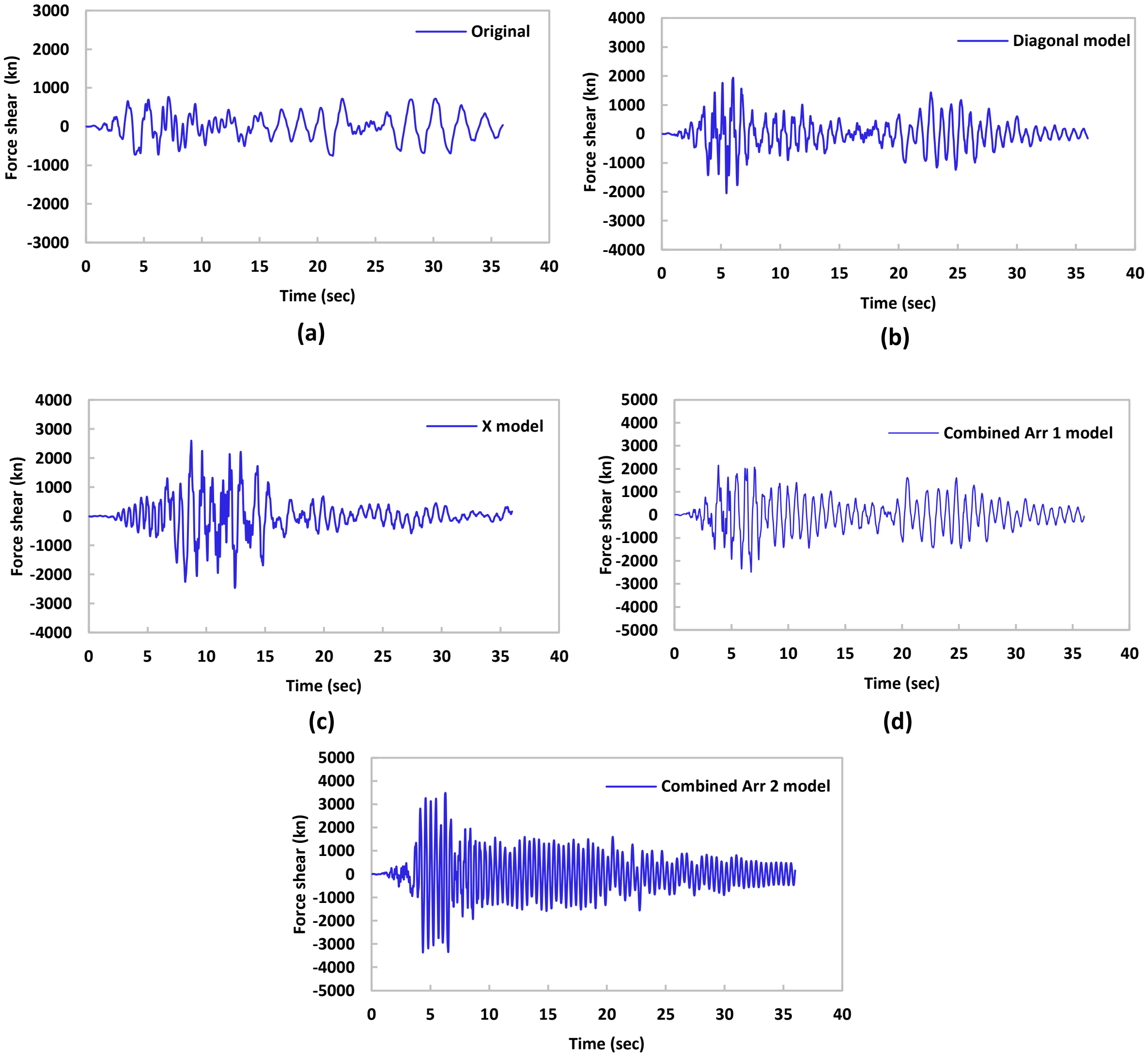
Fruili Italy-01 **Loma Prieta** **Northridge-01**



Average

Figure 10 - The roof displacement for all models under the three selected earthquakes and their average.

<u>Comparison of shear force of all structures:</u> The shear force values of all models under the Fruili Italy-01 earthquake through nonlinear time history analysis are presented in Figure 11.



(a)

(b)

(c)

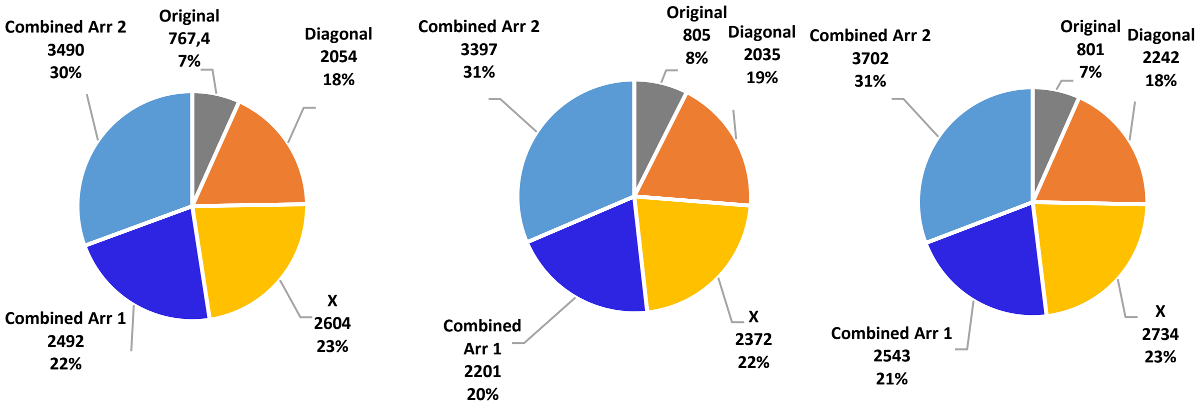
(d)

(e)

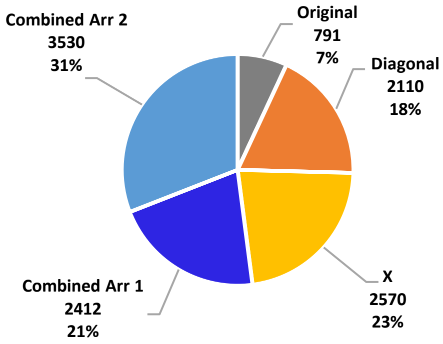
Figure 11 - Time- force shear diagram of all models under Fruili Italy-01 earthquake: (a) Original, (b) Diagonal, (c) X, (d) Combined arrangement 1, (e) Combined arrangement 2.

A comparison of the shear force values in the X direction for all models under the three selected records with their average is illustrated in Figure 12. It is observed that averagely the shear force values exhibited a ratio of 266%, 324%, 304% and 446% for the diagonal, X, combined arrangement 1 and combined arrangement 2 models respectively, compared with the original model.

This finding shows that the presence of a combined brace model with arrangement 2 in buildings can significantly increase the force shear compared to diagonal, X and combined brace using arrangement 1 models. This substantial increase can be explained by the addition of steel braces to the RC structure, which is subject to seismic stresses.



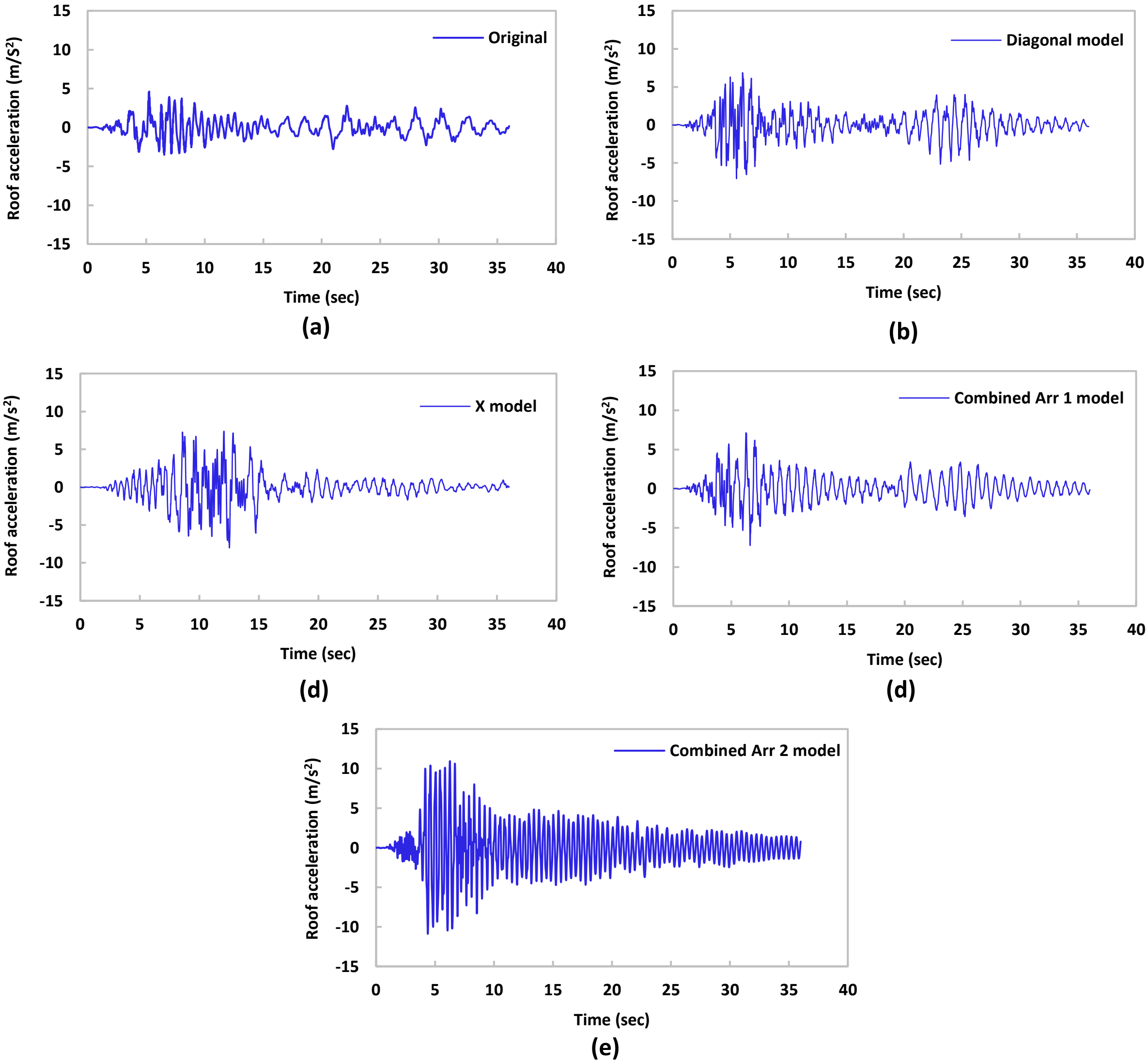
Fruili Italy-01 **Loma Prieta** **Northridge-01**



Average

Figure 12 - Force shear for all models under the three selected earthquakes and their average.

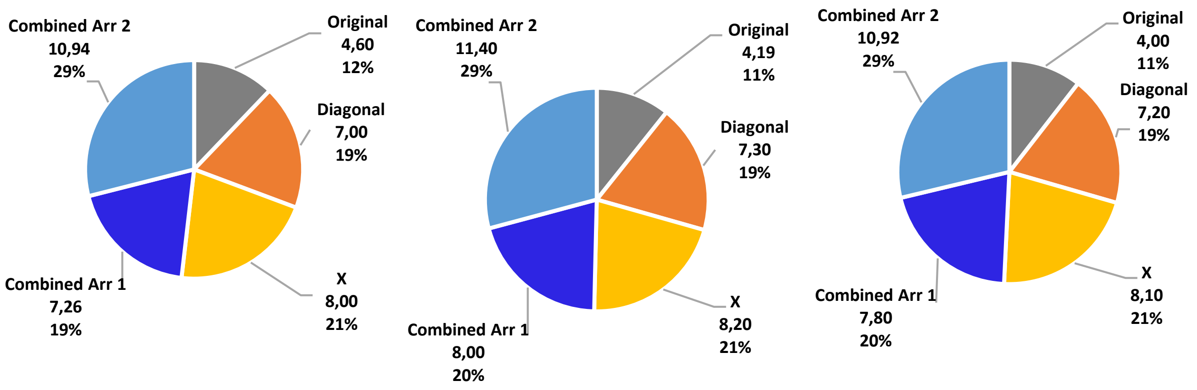
<u>Comparison of roof acceleration of all structures:</u> Figure 13 display the roof acceleration of the structure from nonlinear time history analysis under the Fruili Italy-01 earthquake.



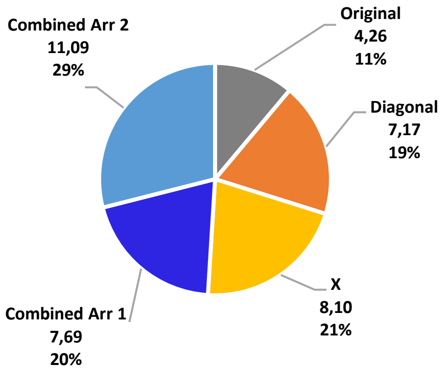
(a) (b) (d) (d) (e)

Figure 13 - Time-roof acceleration for all models under Fruili Italy-01 earthquake: (a) Original, (b) Diagonal, (c) X, (d) Combined arrangement 1, (e) Combined arrangement 2.

A comparison of the roof acceleration values in X direction for all models under the three selected records with their average is depicted in Figure 14. Compared to the roof acceleration of the original model, it is seen that the four model's diagonal, X, combined arrangement 1 and combined arrangement 2 attained a ratio about 168%, 189%, 180% and 260% respectively, with the average values. Based on the results, it could be observed that the presence of X, combined arrangement 1 and combined arrangement 2 braces in buildings can significantly augment the roof acceleration compared to diagonal brace. It can be concluded that steel braces cannot reduce the absolute acceleration of RC structures.



Fruili Italy-01 **Loma Prieta** **Northridge-01**



Average

Figure 14 - Roof acceleration for all models under the three selected earthquakes with their average.

6. Conclusions

This study presents the influence of steel bracing systems as a retrofitting technique to existing reinforced concrete buildings using different types of bracing systems with different arrangements diagonal, X, and combined between diagonal and X braces under tow arrangements. The analytical models were established using SeismoStruct software. The seismic performance of the models was investigated using static pushover and dynamic time history analyses in this paper. the following conclusions have been drawn based on the results obtained from the present study:

- Through the nonlinear static pushover analysis, the results showed that all models could reach a target displacement of 0,30 meter. On the other hand, all four upgrading methods increase the peak base shear, with the maximum observed increase for the combined bracing system using arrangement 2 with 372% and 360%, and the minimum for the diagonal model with 180% and 166% greater than the original model, under uniform and triangular loadings, respectively.
- In the dynamic time history analysis procedure, the obtained average values: the roof displacement while exhibited a ratio about 50%, 41%, 45% and 29 %, the roof shear force exhibited a ratio of 266%, 324%, 304% and 446%, and the roof acceleration exhibited ratios of 168%, 189%, 180% and 260%, with diagonal, X, combined arrangement 1, and combined arrangement 2 models, respectively, compared to the original model. Therefore, this finding shows that the presence of combined brace using arrangement 2 in buildings results in less roof displacement, higher force shear and roof acceleration.

In conclusion, the obtained results show that the seismic behavior of the RC structure can be effectively increased after strengthening by adding diagonal, X, and combined between diagonal and X using tow arrangements of steel braces. Better enhancement can be attained by using the proposed combined system with the second arrangement. Thus, the choice of the kinds of bracing systems and their arrangement is very significant in the response of retrofitted RC structures

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