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THE SEISMIC RESPONSE OF MIXED REINFORCED CONCRETE–STEEL LOW-RISE BUILDINGS UNDER NEAR-FAULT EARTHQUAKES

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Abstract

This work investigates the seismic behaviour of a group of mixed reinforced concrete-steel low-rise buildings, a structural type that is often met in engineering praxis. Specifically, the considered mixed buildings consisting of reinforced concrete (r/c) lower story/ies and a structural steel upper story, are analysed by examining their seismic non-linear response characteristics. Considering the small number of existing research literature for this type of mixed low-rise building frames, as well as the lack of specific recommendations of the current seismic codes for the latter, the investigation of the seismic response of this structural building type appears important. A comparison of the two cases of support condition, i.e. fixed or pinned, of the upper steel story upon the lower r/c story/ies is performed. Near-fault seismic motions are used in the current time-history analyses to force the investigated mixed buildings to exhibit strong nonlinear responses. The conclusions drawn from these non-linear dynamic analyses provide helpful guidelines for the seismic performance design of mixed r/c-steel low-rise frames.

Keywords: Mixed Buildings, Reinforced Concrete, Steel, Non-linear time-history analysis, Near-fault Earthquakes, Seismic Response.

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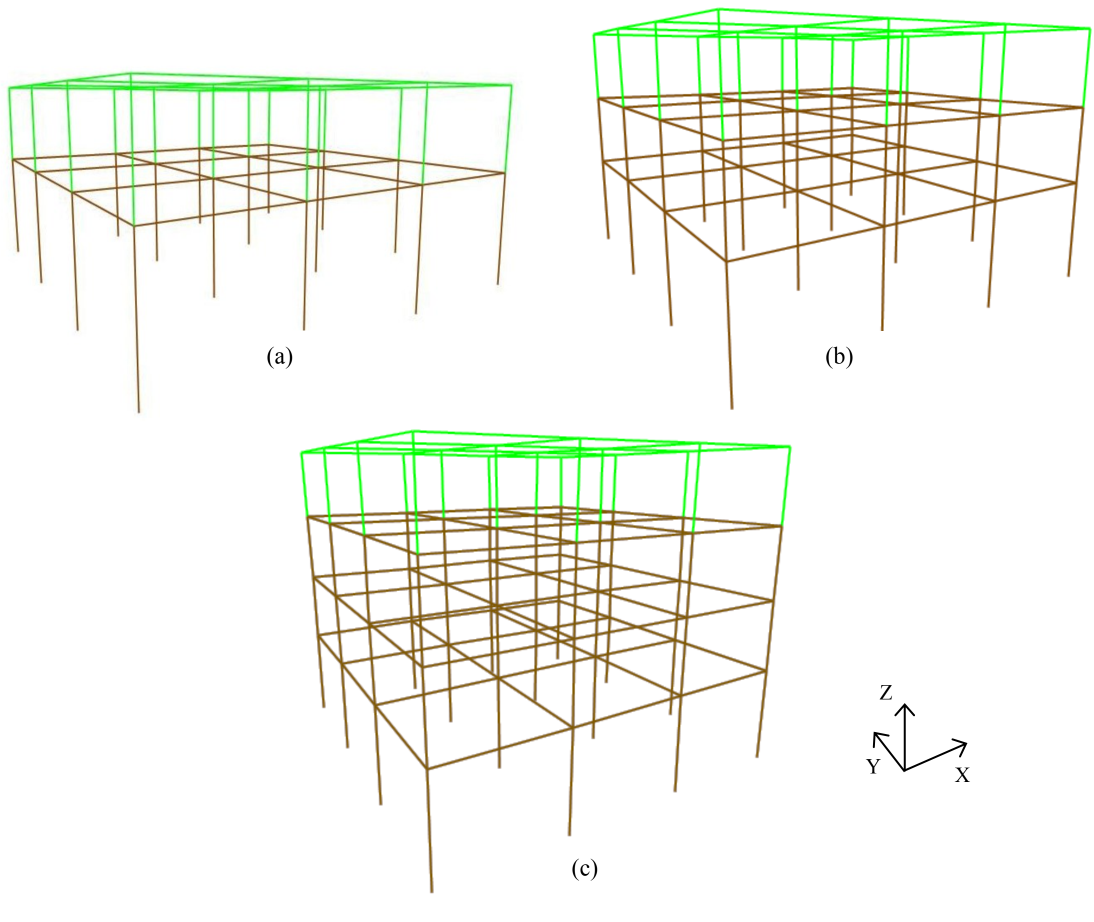
1 INTRODUCTION

According to the current design codes [1], the same structural material is considered for the construction of a whole building frame throughout all stories. Seismic codes usually refer to structures made from one material, such as reinforced concrete (r/c) [2], or steel [3]. However, the case of a steel story added upon an r/c building is often found in everyday construction practice. Neglecting the consideration of the added steel story as a secondary structure [4], i.e. a smaller in mass and weight added steel structure upon an r/c one, the resulting mixed r/c steel building type is examined here, assuming the same size in-plan of the steel and the underlying r/c stories. This paper presents selected the response results of the investigated seismic behaviour of mixed r/c-steel low-rise frames subjected to near-fault earthquakes.

2 DESCRIPTION OF CASE STUDIES AND ANALYSIS

In this work, two-, three- and four-story 3D mixed r/c steel building frames are examined, as shown in Fig. 1, where the lower story/ies are considered to be constructed by r/c and the upper story by steel. The mixed buildings have a square plan with $15.0\times15.0m^2$ dimension consisting of three equal spans of 5.0m in each horizontal direction, X and Y. The r/c bottom story has a height of 4.0m and the upper r/c or steel stories have a height of 3.0m. The diaphragm action of each floor is considered due to r/c and composite slabs on each floor with a thickness of 0.15m.



(a) (b) (c)

Figure 1: (a) Two-, (b) three- and (c) four-story mixed r/c-steel 3D frames under study (lower r/c stories and upper steel story with brown and green colours respectively) with the global coordinate system.

In all mixed frames, the material assumed for the r/c part is concrete C25/30 with steel reinforcement B500c, and for the steel part is structural steel S355. A dead load of 5.0 kN/m^2 is applied on the floors and 3.0 kN/m on walls [5]. A live load of 2.5 kN/m^2 is applied on r/c or composite slabs [5]. The mixed building frames are dimensioned according to the current seismic codes [1] for medium ductility class (DCM) using the typical rigid soil assumption with the following design spectrum considerations: zone ground acceleration 0.36g, importance factor 1.0, viscous damping ratio 5% and soil type C. The maximum values of the behaviour factor according to [1] for DCM are considered as 3.9 for the r/c part and 4.0 for the steel part of the mixed frames. The combination rule of 30% [1] is followed in the seismic loading calculations in both horizontal directions, considering as well an accidental eccentricity of 5%. The seismic design calculations are performed separately for the r/c part and the steel one by the aforementioned assumptions, considering the damage limits for non-structural elements of brittle materials [1]. The final dimensioned sections for beams and columns of the mixed buildings are shown in Table 1. The orientation of the steel columns is shown in Fig. 2, selected to form a strong perimetrical steel frame.

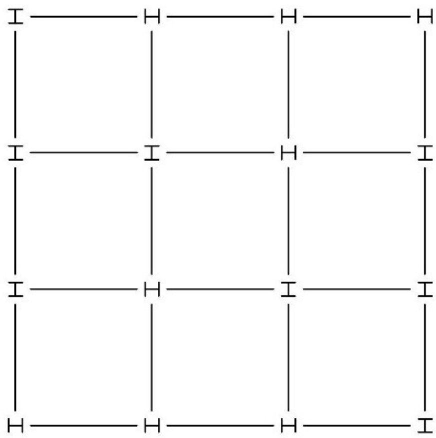


Figure 2: The in-plane orientation of the steel columns of the steel story.

Two-story mixed building			Columns			Beams		
story number	story height (m)	material	cross-section dimensions (cm/cm)	longitudinal reinforcement	stirrups	cross-section dimension (cm/cm)	longitudinal reinforcement	stirrups
1	4.0	r/c	50/50	8Φ22	Φ8/10	25/60	8Φ18	Φ8/10
2	3.0	steel		HEA 360			IPE 270	
Three-story mixed building			**Columns**				**Beams**	
story number	story height (m)	material	cross-section dimensions (cm/cm)	longitudinal reinforcement	stirrups	cross-section dimension	longitudinal reinf/ment	stirrups
1	4.0	r/c	55/55	16Φ20	Φ8/10	25/60	8Φ20+8Φ10	Φ8/10
2	3.0	r/c	50/50	8Φ20+8Φ10	Φ8/10	25/60	8Φ18	Φ8/10
3	3.0	steel		HEA 360			IPE 270	
Four-story mixed building			**Columns**				**Beams**	
story number	story height (m)	material	cross-section dimensions (cm/cm)	longitudinal reinforcement	stirrups	cross-section dimensions (cm/cm)	longitudinal reinforcement	stirrups
1	4	r/c	60/60	16Φ20	Φ8/10	25/70	8Φ20+8Φ10	Φ8/10
2	3	r/c	60/60	8Φ20+8Φ16	Φ8/10	25/70	8Φ20+8Φ10	Φ8/10
3	3	r/c	50/50	8Φ20+8Φ10	Φ8/10	25/60	8Φ18	Φ8/10
4	3	steel		HEA 360			IPE 270	

Table 1: Dimensioning of columns and beams of the mixed building two-, three- and four-story frames.

Regarding the support of the steel story upon the r/c part of the mixed buildings, the following two boundary conditions are considered: (a) a fixed support of the steel columns leading essentially to biaxial moment excursions, (b) a called as "fixed-pinned" support of the steel columns, indicating a fixed behaviour in the cross-section major axis and a pinned behaviour in the cross-section minor axis. These (a) and (b) boundary conditions represent the design of the column-base connection in terms of the base plate, anchor rods, and embedment into the concrete column. In both examined supporting conditions, the dimensioning of the mixed buildings is the same for comparison reasons.

The mixed frames are investigated by non-linear time history (NLTH) analysis by SAP2000 software [6] under the near-fault ground motions described in Table 3 as downloaded by [7]. In Table 3, the name, location, year, moment magnitude M_w and the peak ground acceleration (PGA) of each earthquake are provided, where more relevant information is available in [7]. As shown by various literature works, indicatively mentioned Refs. [8-9], the earthquake incidence angle may affect the structural response. In the current work, the considered angles of the ground motions are along the major horizontal axes, as shown in Figure 1, which are 0^o and 90^o. The elastoplastic behaviour or r/c and steel elements is considered in the current NLTH analyses through the application of point hinges at the ends of all elements ends following the recommendations of ASCE 41-17 [10].

Name and Year of each earthquake	Earthquake name in response plots	M_w	PGA (g)
Landers, 1992	LANDERS	7.3	0.81/0.73
San Fernando, 1971	PACO	6.6	1.17/1.08
Cape Mendocino, 1992	PETROLIA	6.9	0.66/0.59
Loma Prieta, 1989	LOS GATOS	7.0	0.56/0.61
Chi-Chi, 1999	TAIWAN	7.6	0.50/0.36
Kefalonia, 2014	KEFALONIA	6.1	0.67/0.60
Tabas, Iran, 1978	TABAS	7.1	0.93/1.10
Superstition Hills, 1987	HILLS	6.5	0.45/0.38
Northridge, 1994	SYLMAR	6.7	0.37/0.58
Kobe, 1995	KOBE	6.9	0.61/0.62
Imperial Valley, 1979	ARRAY	6.5	0.34/0.46

Table 2: Earthquakes used in the NLTH analyses of the mixed frames.

A selected one value of the damping ratio of the whole mixed frame is necessary for the NLTH analyses [11], however, this value is not provided for mixed buildings by the current regulations [1-3]. Following the procedure proposed by Sivandi-Pour et al. [12], a uniform value of damping ratio is calculated here for each mixed building considering the first few modes of modal analysis, as shown in next Table 3.

Mixed frame	Damping ratio
Two-story	4.57 %
Three-story	4.33 %
Four-story	3.63 %

Table 3: Uniform damping ratio values used in the NLTH analyses of the mixed frames shown in Figure 1.

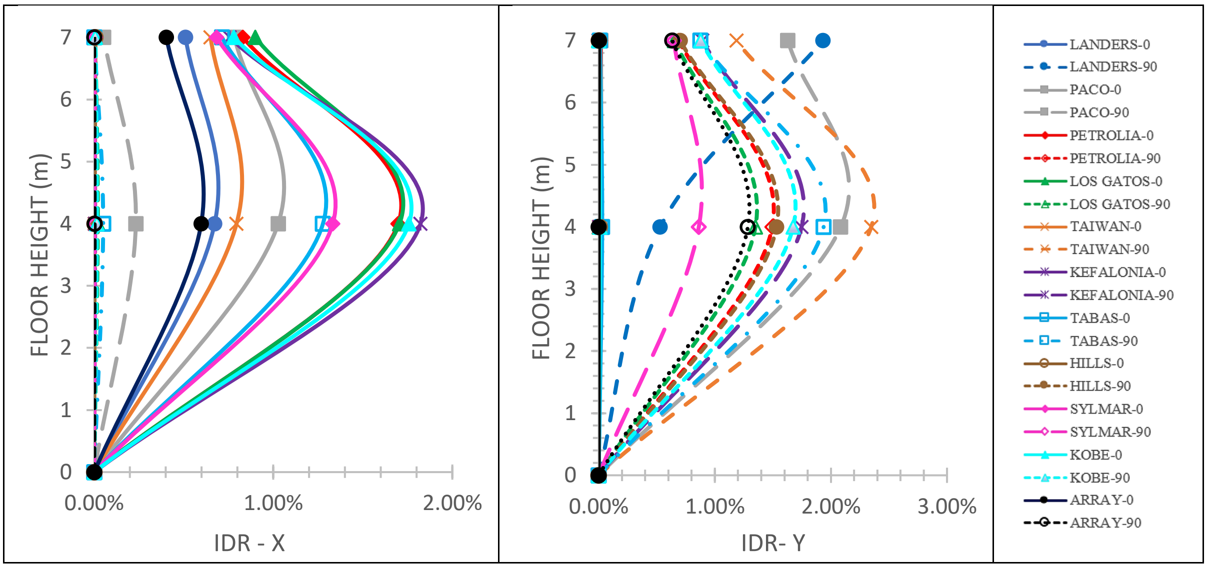
3 NUMERICAL RESULTS AND DISCUSSION

In this section, the numerical results of the mixed frames NLTH analyses under the ground motions of Table 2 are shown and discussed. Due to space limitations selected plots are presented here concerning the maximum interstory drift ratio (IDR) for each earthquake of the mixed frames of Figure 1 on the two horizontal axes, X and Y, along the building height. For evaluation purposes, the following IDR plots are compared to the IDR limit values for the seismic performance levels of [13], as mentioned here for convenience. Regarding moment resisting frames (MRFs) by r/c or steel, the IDR value of 0.5% corresponds to the limit of Fully Operational (FO) performance level, 1.5% refers to the Immediate Occupancy/operational (IO) performance level, 2.5% refers to Life Safety (LS) performance level, and 3.8% refers to Near Collapse (NC) performance level [13]. In the presented IDR plots, each earthquake label is followed by 0 or 90 referring to the earthquake incidence angle of 0º and 90º, respectively, for brevity reasons.

Concerning the two-story mixed building with the fixed connection of the steel story on the r/c one, as in Figure 3, the maximum IDR values are within the limit of LS performance level in the X axis, and, respectively, within the NC level in the Y axis. The maximum values of IDR are observed at the top of the 1st story in both axes, such as up to 1.82% for the X axis and 2.35% for the Y axis (Fig. 3).

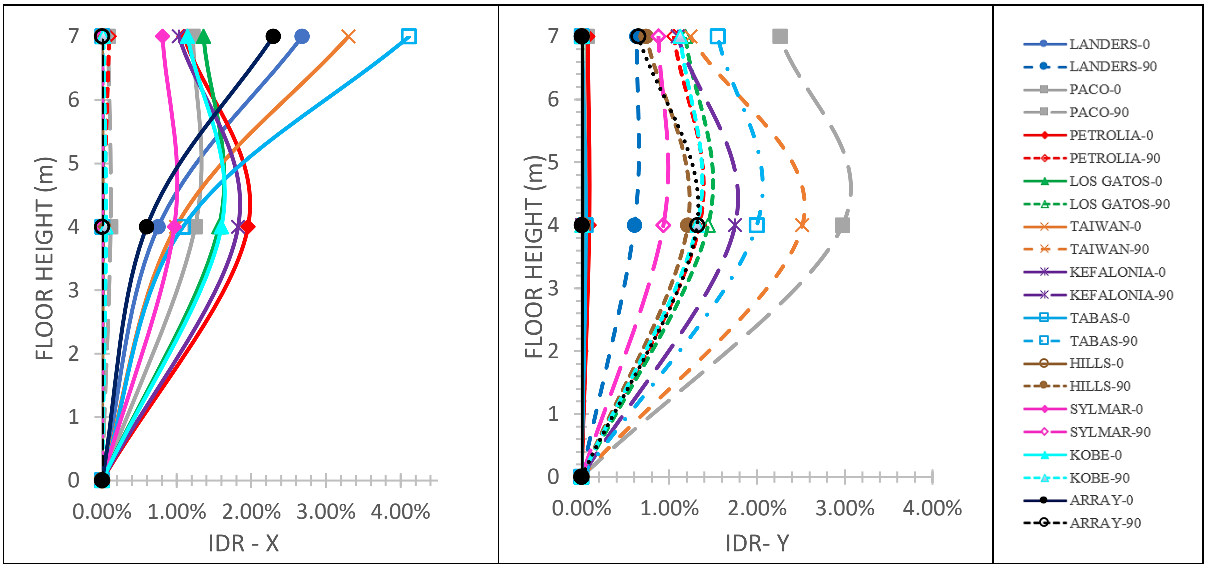
Regarding the fixed-pinned connection of the steel story on the r/c one of the two-story mixed building, greater values of IDR are observed in both X and Y axes, (Fig. 4) as compared to the respective plots for the fixed connection in Fig. 3. In Fig. 4a, the maximum IDR values are observed at the top of the steel story, even up to 4.11% within the limit of NC level [13]. In Fig. 4b, the maximum IDR values are observed on the Y axis at the top of the 1st story, up to 2.98%.

Comparing the IDR plots of the two-story mixed frame in both axes (Figs. 3-4), the IDR values in the X axis are greater for the considered earthquakes with incidence angle 0º, than for the angle of 90º for the same earthquakes. Respectively, the IDR values in the Y axis are greater for these earthquakes with incidence angle 90º, than for the angle 0º.



(a) (b)

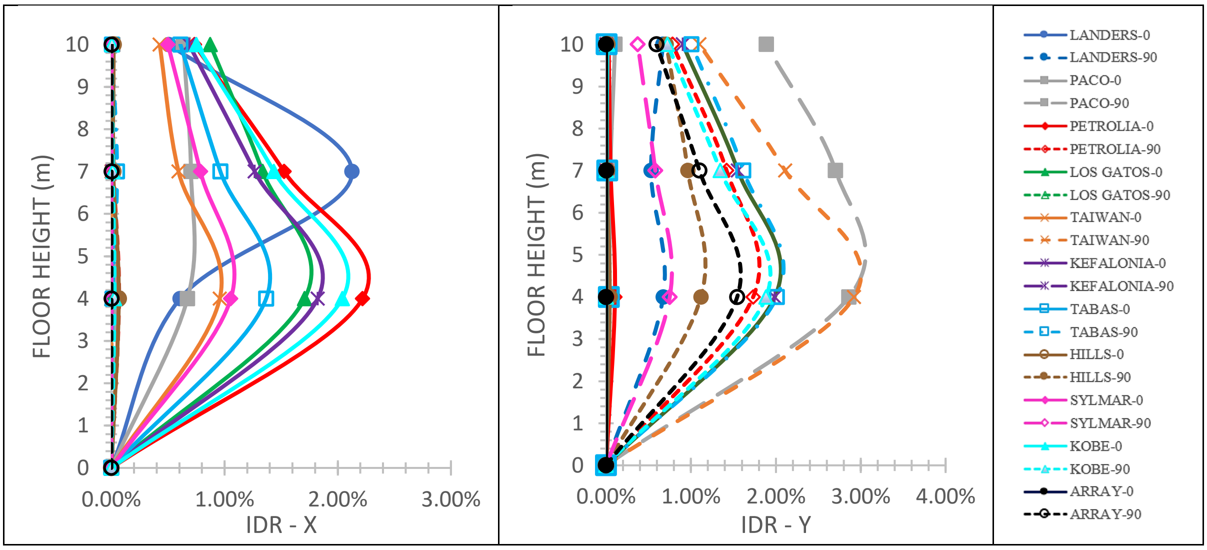
Figure 3: IDR on the (a) X and (b) Y axes for the fixed connection of the steel story on the r/c one of the two-story mixed building.



(a) (b)

Figure 4: IDR on the (a) X and (b) Y axes for the fixed-pinned connection of the steel story on the r/c one of the two-story mixed building.

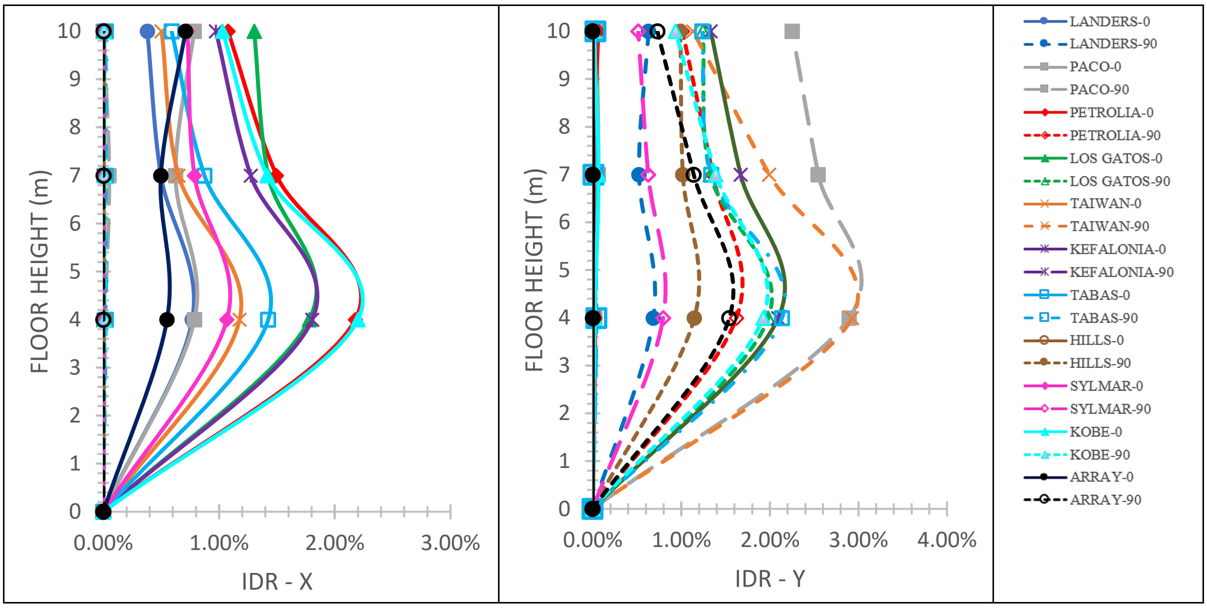
At the three-story mixed building for the fixed connection of the steel story on the r/c ones, as in Fig. 5a, the values of IDR in the X axis are within the limit of LS performance level, with a maximum value of 2.22%. Respectively, as observed in Fig. 5b, the values of IDR in the Y axis are within the limit of NC performance level with a maximum value of 2.92%. In Figs, 5a-b, the data for the seismic motions “Los Gatos” with angle 90º and “Array” with angle 0º are not shown due to IDR values greater than the limits of [13] indicating building failure.



(a) (b)

Figure 5: IDR on the (a) X and (b) Y axes for the fixed connection of the steel story on the r/c ones of the three-story mixed building.

Concerning the fixed-pinned connection for the three-story mixed building, the values of IDR on the X axis are within the limit of LS performance level up to 2.2%, as in Fig. 6a, where the maximum values for each earthquake are observed at the top of the 1st story. Respectively, the values of IDR on the Y axis are observed to be within the limits of NC performance level in Fig. 6b, up to 2.93%. Similar maximum IDR values are observed in Figs. 5-6 for both support types of the steel story on the r/c ones, while more building failures due to large IDR values are observed for the fixed support, as compared to the fixed-pinned support.

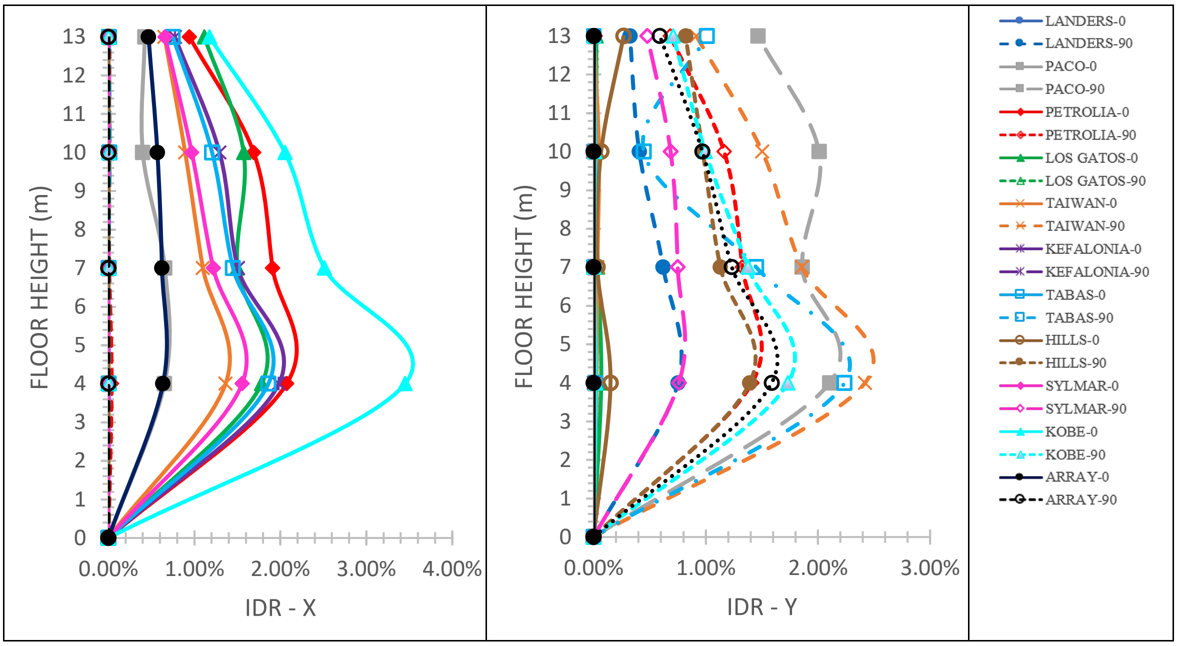


(a) (b)

Figure 6: IDR on the (a) X and (b) Y axes for the fixed-pinned connection of the steel story on the r/c ones of the three-story mixed building.

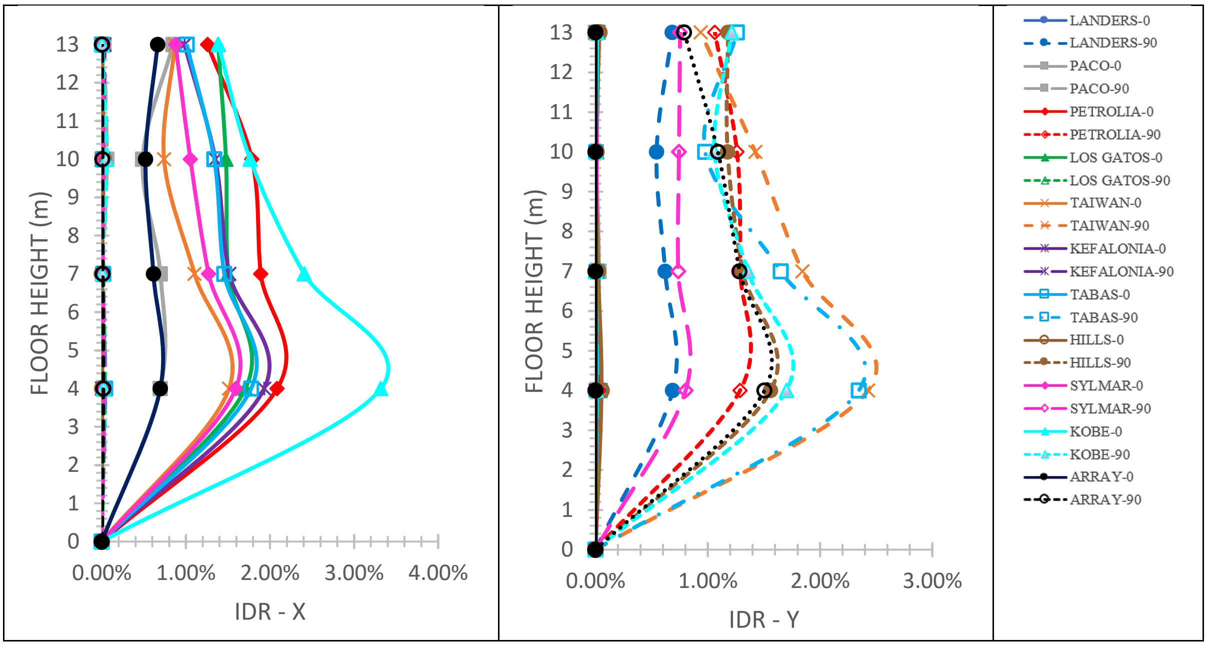
At the four-story mixed building, as shown in Figs. 7-8, the greater IDR values in both X and Y axes are observed at the top of the 1st story, in the range value of NC performance level. Considering the fixed support of the steel story on the r/c ones, as in Fig. 7, the maximum IDR observed is 3.45% on the X axis and 2.42% on the Y axis. At the building top, the maximum IDR is 1.18% on the X axis (Fig. 7a), and 1.47% on the Y axis (Fig. 7b). In Fig. 7, concerning the four-story mixed buildings with the fixed supporting condition, due to IDR values beyond the limit of NC performance level [13], the IDR plots for the seismic motions “Landers” with incidence angle 0^o, “Los Gatos” with angle 90^o and “Kefalonia” with angle 90^o are not shown.

As shown in Fig. 8 for the fixed-pinned support of the steel story on the r/c part, the maximum IDR is 3.32% in the X axis and 2.43% in the Y axis, with similar values as for the fixed support as in Fig. 7. At the building top, the maximum IDR values, as observed in Fig. 8, are 1.39% in the X axis and 1.21% in the Y axis. In the four-story mixed buildings with the fixed-pinned support (Fig. 8), due to exceedance of the IDR limits of NC performance level [13], there are left out the IDR response data of the seismic motions “Landers” with incidence angle 0^o, “Los Gatos” with angle 90^o, “Kefalonia” with angle 90^o and “Paco” with angle 90^o. Thus, more damage and building failures are observed for the fixed-pinned support condition, compared to the fixed support of the steel story on the r/c part of the mixed building. Similarly to the previous Figs. 5-8, greater values of IDR are observed in the X axis for the ground motions with incidence angle 0^o, and respectively in the Y axis for these ground motions with incidence angle 90^o.



(a) (b)

Figure 7: IDR on the (a) X and (b) Y axes for the fixed connection of the steel story on the r/c ones of the four-story mixed building.



(a) (b)

Figure 8: IDR on the (a) X and (b) Y axes for the fixed-pinned connection of the steel story on the r/c ones of the four-story mixed building.

4 CONCLUSIONS

This work aims to investigate the seismic response of simple mixed r/c-steel building structures under near-fault seismic motions. The presented IDR plots have general values over the Fully Operational performance level [13] leading to a strong inelastic response of the mixed buildings being observed from the NLTH analyses of the selected strong ground motions. From the presented response IDR plots of the mixed r/c-steel 3D frames in comparison to the seismic performance levels [13], the following conclusions can be stated.

- The consideration of the fixed-pinned support of the steel story on the r/c part of the mixed building tends to result either in an increased IDR range of values (for either one or both r/c and steel parts) or in a greater number of building failures, as compared to the fixed support condition. Thus, the fixed-pinned support appears as more detrimental to the seismic structural response of the mixed building, as compared to the fixed support.
- At the level of the interconnection of the steel story on the r/c part, a greater IDR range of values by 18~40% is observed for the fixed connection still within the limit of LS performance level, as compared to the fixed-pinned support, respectively.
- The mixed buildings present general IDR values within the limits of the NC performance level, which indicates a general structural behaviour within the guidelines of the current seismic codes.
- The steel story of the mixed buildings tends to exhibit elastic behaviour with smaller IDR values, while the r/c part is stressed more showing greater IDR values at the top of the 1st story, as compared to the whole mixed building. This indicates that the usual addition of a steel story upon an r/c part burdens the r/c part of the resulting mixed building.

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