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SEISMIC PERFORMANCE OF REINFORCED CONCRETE FRAMES EXTERNALLY REINFORCED WITH SHAPE MEMORY ALLOY BARS

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Abstract: Pre-1970s designed and built reinforced concrete frame structures are considered unsafe when subjected to seismic loads. Insufficient anchorage of the beam reinforcement in the joint area of the beam-column joints of these structures is considered a main deficiency. Newly built frame structures are seismically designed for safety, where high inelastic deformations are allowed to occur under moderate to strong earthquakes. Minimizing these inelastic deformations make the structure repairable. One way to minimize these residual deformations is by using smart materials such as superelastic Shape Memory Alloys (SMAs). In this paper, the seismic performance of RC frames retrofitted using external superleastic SMA bars is investigated and compared to the behaviour of a regular steel RC frame structure. Nonlinear time history analysis is performed for a six storey RC frame structure located in high seismic region. After performing the analysis, two retrofitted frames are assumed. Analysis is performed again for the two frames at the load intensities causing failure of the steel RC frame. The performance of the retrofitted frames is compared to the steel RC frame in terms of the Maximum Inter-storey Drift (MID) ratio, Maximum Residual Inter-storey Drift (MRID), Maximum Roof Drift Ratio (MRDR), and Residual Roof Drift Ratio (RRDR).

1 INTRODUCTION

Reinforced Concrete (RC) frame structures designed and built prior to the 1970s are considered not ductile, and thus unsafe under seismic loads (Hassan 2011). The beam-column joints (BCJs) of these structures are poorly detailed and are considered deficient under lateral loads. Beam reinforcement is insufficiently anchored into the joint area of the BCJs of these structures.

Newly built RC frame structures are designed to dissipate the energy of moderate and strong earthquakes through allowing some inelastic deformations (Engindeni 2008). These inelastic deformations result in permanent deformations in the structure, and in some cases s seismically damaged structure may need to be demolished and replaced. Thus, there is a need to retrofit the pre 1970s structures to be able to resist the seismic loads, and to reduce the permanent deformations of the newly built structures. One of the methods to achieve this goal is by utilizing smart materials such as superelastic Shape Memory Alloys (SMAs) (Alam et al. 2009, Youssef and ElFiki 2012).

Superleastic SMA bars have unique properties compared to the usual steel reinforcement. They have the ability to undergo large deformations and return to their undeformed shape upon unloading (Alam et al. 2007). They also have good resistance to fatigue and corrosion and high damping ability (Janke et al. 2005). So using superleastic SMA bars to enhance the seismic performance of these structures can be ideal (Alam et al. 2009, Youssef and ElFiki 2012).

Youssef and Elfiki (2012) studied the behaviour of RC frame structures internally reinforced with SMA bars at the critical locations of the structure. Seven different arrangements for the SMA bars are selected resulting in seven different frames. Nonlinear dynamic analyses are performed to select the frames with the best seismic performance. It is found that the frames with SMA reinforcement in the BCJs of the first floor, and in the BCJs of the first and fourth floors give the best seismic performance.

This paper investigates the seismic performance of RC frame structures retrofitted using external superleastic SMA bars. A six storey steel RC frame located in high seismic region is used as the reference frame. Two potential retrofit schemes that utilize superelastic SMA bars are assumed. Nonlinear dynamic analyses are performed for the three frames using Seismistruct software (Seismostruct 2018). Results of the analysis are then used to compare the seismic performance of the three frames in terms of the Maximum Inter-storey Drift (MID) ratio, Maximum Residual Inter-storey Drift (MRID), Maximum Roof Drift Ratio (MRDR), and Residual Roof Drift Ratio (RRDR).

2 PROPOSED RETROFITTING TECHNIQUE

The idea of the proposed retrofitting technique is based on attaching external SMA bars to the RC BCJ. As shown in Figure 1, the bars are attached to the BCJ using external steel angles. The steel angles are attached to the BCJ using steel bolts. One angle is attached to the BCJ joint area, while the second angle is attached to the beam. Hold down plates can be used for big lengths of the SMA bars to enforce the bears to deform with the beam.

The modulus of elasticity of SMA is much lower (1/5 to 1/3) than that of the regular steel. Thus, attaching a small to moderate ratio of SMA will improve the strength and the stiffness of the BCJ, but it is not expected to reduce the residual deformations at complete unloading. Thus, it is proposed to cut the internal steel bars of the beam at the face of the column. This ensures that the BCJ behaviour is governed by the external SMA bars rather than the internal steel bars, and thus minimum residual deformations are expected at complete unloading. The effect of the steel cut bars on the beam stiffness and strength will be recovered through increasing the amount of external SMA bars.

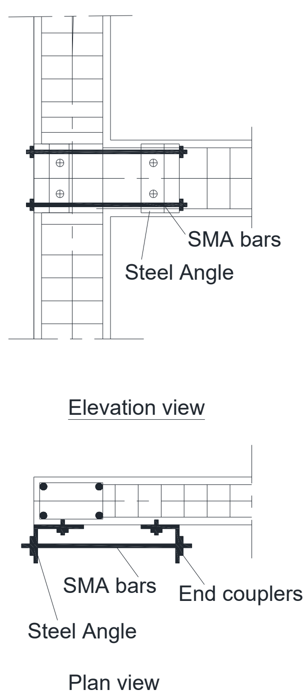


Figure 1: Proposed retrofitting technique

3 SIMPLIFIED MODEL

A simplified model for the retrofitted BCJ is proposed in this section. The simplified model is developed using Seismostruct software v.6 (Seismostruct 2018). The special technique used to model the connection include: (i) modelling the SMA bars using inelastic truss elements; (ii) modelling the superelastic behaviour of the SMA bars using the uniaxial material model proposed by Auricchio and Sacco (1997); (iii) modelling the concrete beam and column using displacement based inelastic frame elements; and (iv) modelling the external angles that supports the SMA bars using rigid arms connected to the concrete beam and column.

As shown in Figure 2, the beam and the column of the BCJ are modelled using frame elements. Two rigid arms are connected to the beam near the face of the column representing the angle supported in the joint area. Another two rigid arms are connected to the beam at a distance equal to the length of the required SMA bars. The SMA bars are connected between the rigid arms and are modelled using truss elements. The reinforcement in the beam element is cut in between the rigid arms to eliminate any contribution from it to the strength, stiffness and residual deformation of the joint. A short cross-section with the same beam dimensions and no steel bars is used to model the real bar cut.

To validate the assumed simplified model, a comparison between the load-displacement results of the simplified model developed using Seismostruct software and the actual model developed using ABAQUS (ABAQUS 2018) is shown in Figure 3. Good agreement between the two results is achieved. The slight difference in the unloading curve can be attributed to: the difference in the element type; and the difference in the used concrete and SMA models.

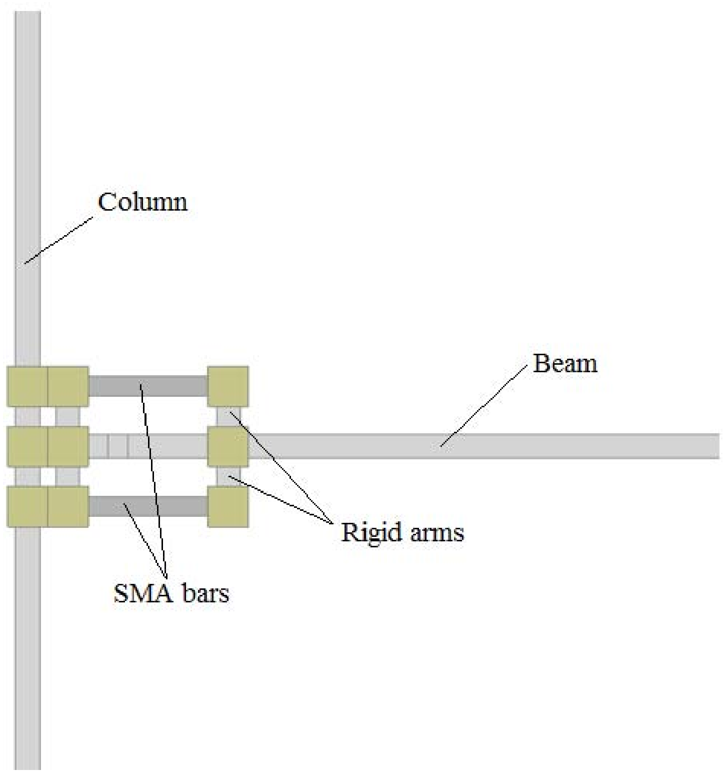


Figure 2: Sketch of the simplified model

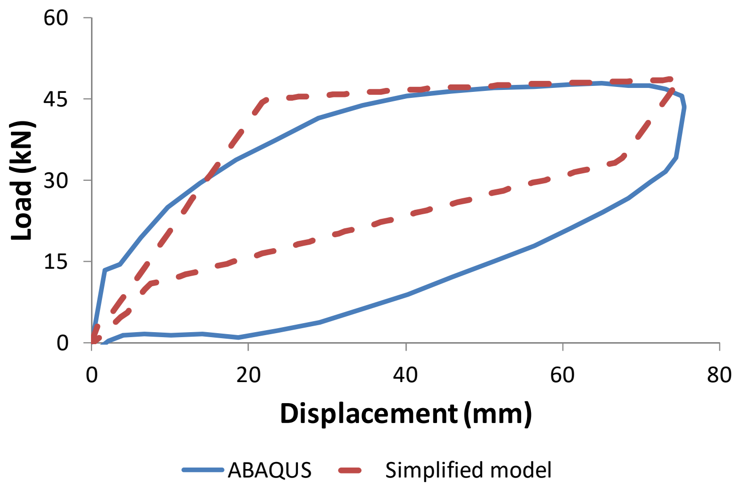
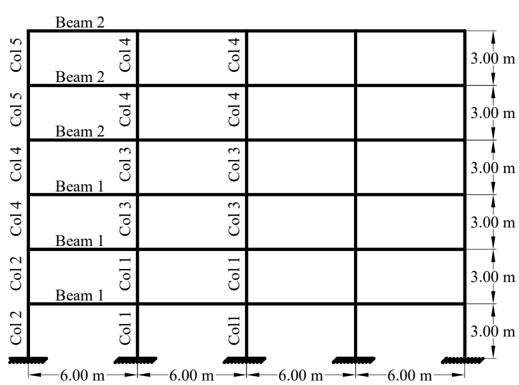


Figure 3: Load-displacement results of the ABAQUS model vs. the simplified Seismostruct model

4 STEEL RC FRAME CHARACTERISTICS AND MODELING

The steel RC frame structure designed by Youssef and Elfeki (2012) is used as the reference frame. The frame (Frame 1) is a symmetric six-storey RC office building located in California (high seismic region). The layout and dimensions of the building are shown in Figure 4. It is designed to satisfy the requirements of the International Building Code (IBC 2006) and the American Concrete Institute (ACI 318 2005). The lateral load resisting system is composed of special moment frames. The cross-section dimensions and the reinforcement details of the frame are shown in Figure 5.

Only one special moment frame is selected for the analysis because of the geometrical symmetry. The frame is modeled using Seismostruct software (Seismostruct 2018). The beams and columns are modeled using cubic elasto-plastic elements. The beams are divided in six elements, while the columns are divided in three. The beams are modeled as T-sections, while the beam-column joints are modeled using rigid elements. The concrete compressive strength is assumed to be 28 MPa while the steel yielding stress is 400 MPa.



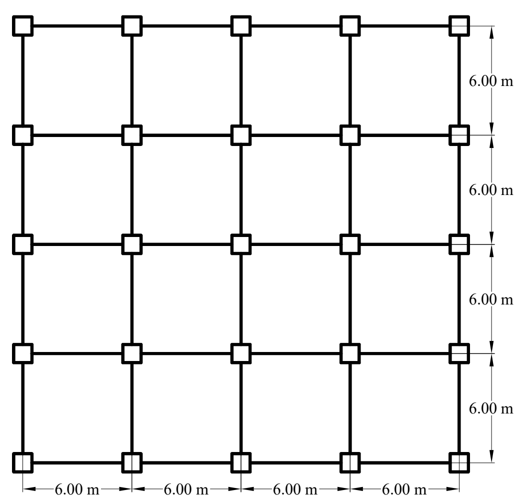


Figure 4: Six-storey RC building Plan and Elevation (Youssef and Elfeki 2012)

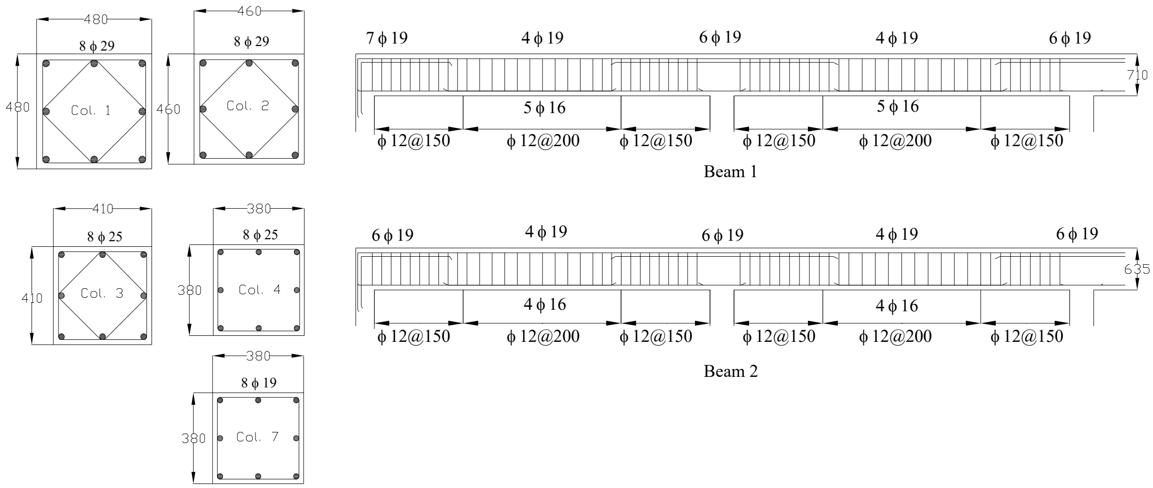


Figure 5: Six-storey RC building Cross sections of beams and columns (Youssef and Elfeki 2012)

5 SMA RC FRAMES

Superleastic SMA bars are added to the steel RC frames to enhance its seismic performance. The SMA bars are added to the beam-column joints of the first floor for one frame (Frame 2) and to the beam-column joints of the first and fourth floors of the other frame (Frame 3). The choice of these locations is based on the recommendations made by Youssef and Elfeki (2012).The internal steel reinforcement of the retrofitted BCJ is cut. This will ensure that the behaviour of the retrofitted BCJs and frame is controlled by the superleastic SMA bars rather than the internal steel bars.

The amount of SMA reinforcement is chosen equal to the amount of internal steel reinforcement. The critical stress, critical strain, modulus of elasticity of the SMA bars is equal to 401 MPa, 0.007, 62.5 GPa respectively. The SMA bars are attached to the frame using external rigid steel angles and bolts. The retrofitted BCJs are modelled in the Seismostruct software using the simplified model.

6 LOCAL FAILURE AND COLLAPSE LIMITS

Local yielding of the RC element is assumed to happen when the reinforcement reaches its yielding strain. Yielding strain is defined as 0.002 for steel and as 0.007 for SMAs. Researchers are suggesting different definitions for the failure of concrete. In this paper, Crushing of concrete is assumed to occur either when the confined concrete reaches a value of 0.015 or when the stirrups reach their fracture strain as proposed by Pauley and Priestley (1992). Collapse of the structure is assumed to occur when four of the columns located in the same storey reach their crushing strain (Youssef and Elfeki 2012).

7 DYNAMIC ANALYSES

7.1 Eigen Value Analysis

Eigen value analysis is performed for the steel RC frame by Youssef and Elfeki (2012). The fundamental period of vibration of the structure is found to be 0.501. The Eigen value analysis is repeated for the two retrofitted frames to investigate the effect of adding external SMA bars on the fundamental period of vibration. No or negligible effect is observed.

7.2 Selection of Ground Motion Records

The five ground motion records used by Youssef and Elfeki (2012) are used in this study to perform the dynamic analysis of the frames. The ratio between the peak ground acceleration and the peak ground velocity (A/v) is used to classify the intensity of the used records. These records cover a wide range of ground motion frequencies. A summary of the records characteristics are given in Table 1. The 5% damped spectral acceleration at the fundamental period of the structure [Sa(T1,5%)] is used to scale the used earthquake records. Figure 6 shows the scaled earthquake records.

Table 1: Chosen earthquake records

Earthquake	Date	Ms Magnitude	Station	PGA (g)	A/v
Northridge USA	17/1/94	6.7	Arleta-Nordhoff	0.340	Inter.
Imperial Valley USA	15/10/79	6.9	El Centro Array #6 (E06)	0.439	Low
Loma Prieta USA	18/10/89	7.1	Capitola (CAP)	0.530	High
Whittier USA	1/10/87	5.7	Whittier Dam	0.316	High
San Fernando	9/2/71	6.6	Pacoima Dam	1.230	Inter.

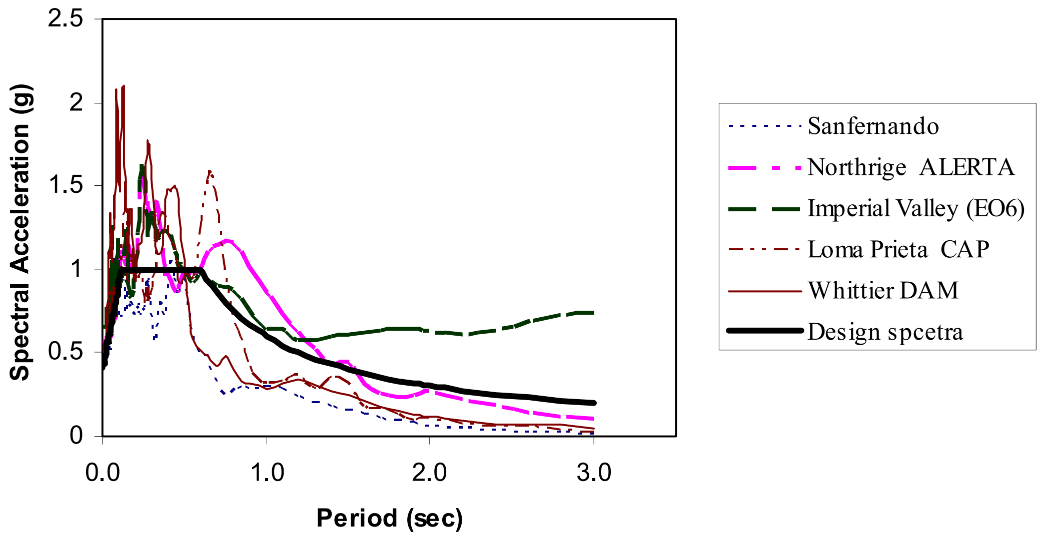


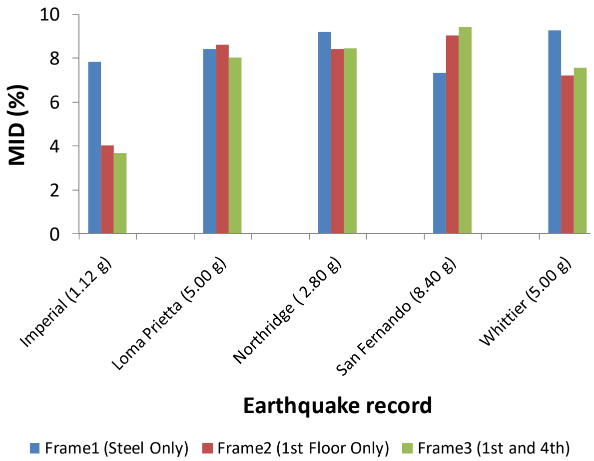
Figure 6: Spectral acceleration diagrams

7.3 Time History Analysis

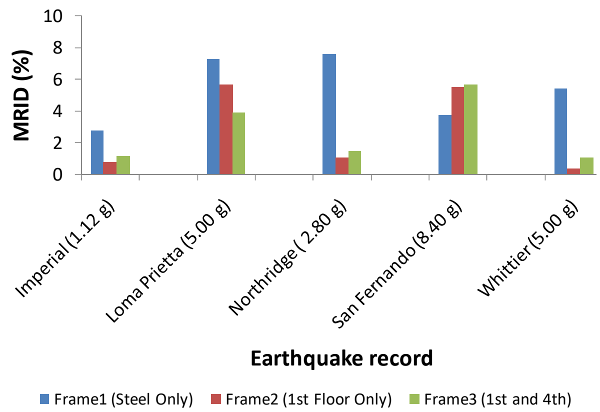
The analysis is first performed for Frame 1 (steel RC frame) to determine the intensities of the five earthquakes at which collapse occur. The analysis is then performed for the other two frames at these intensities. Performance of the three frames is illustrated in the following section.

8 RESULTS AND DISCUSSIONS

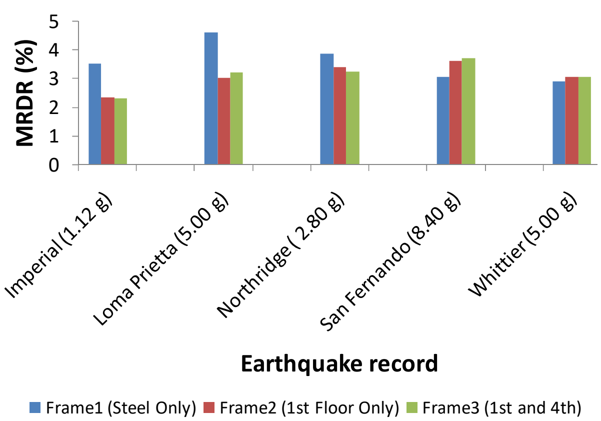
MID, MRID, MRDR, and RRDR values at failure are used in this section to compare the behaviour of the three frames. Results of the three frames are given in Table 2 and are illustrated in Figure 7. The average MID for Frame 1 (steel RC frame) is found to be 8.40%. Frames 2 and 3 have lower average MID values by 11.20% and 11.63%, respectively. This shows the improvement in the frame behaviour by reducing the MID ratio.



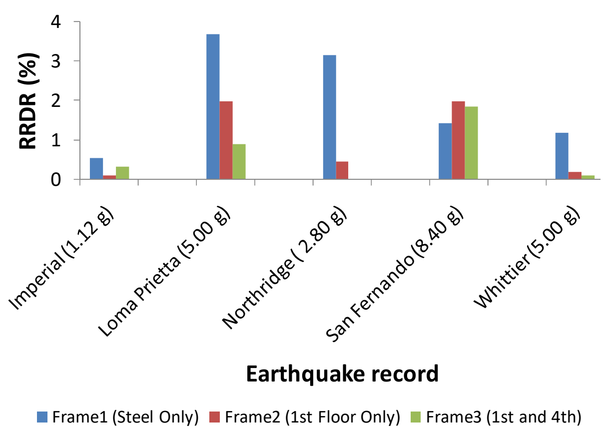
(a) MID



(b) MRID



(c) MRDR



(d) RRDR

Figure 7: Maximum and residual drift ratios of the studied frames

Table 2: Comparison between the seismic performance of the three frames

Earthquake Record	Frame1 (Steel Only)				Frame2 (1st Floor Only)				Frame3 (1st and 4th)			
	MID	MRID	MRDR	RRDR	MID	MRID	MRDR	RRDR	MID	MRID	MRDR	RRDR
Imperial (1.12 g)	7.83	2.77	3.50	0.53	4.01	0.81	2.33	0.08	3.68	1.17	2.29	0.31
Loma Prietta (5.00 g)	8.41	7.25	4.60	3.68	8.60	5.66	3.01	1.96	8.02	3.89	3.21	0.88
Northridge (2.80 g)	9.18	7.56	3.85	3.15	8.43	1.05	3.37	0.44	8.45	1.47	3.23	0.01
San Fernando (8.40 g)	7.33	3.77	3.04	1.42	9.04	5.52	3.61	1.97	9.43	5.64	3.71	1.83
Whietter (5.00 g)	9.26	5.43	2.89	1.17	7.22	0.36	3.05	0.18	7.55	1.08	3.04	0.09
Average Value	8.40	5.36	3.57	1.99	7.46	2.68	3.08	0.93	7.43	2.65	3.10	0.62
Percent of Change	NA	NA	NA	NA	-11	-50	-14	-54	-12	-51	-13	-69

The improvement in the MRID value for frames 2 and 3 is found to be significant. The average MRID values of Frames 2 and 3 are 2.68% and 2.65% which are much lower (50.00% and 50.51%) of that of Frame 1 (5.36%). These values illustrate the significant improvement in the frame behaviour by adding the external SMA bars to the frame at the right locations.

The average MRDR is found to be 3.57% for Frame 1. This value is reduced by 13.96% for Frame 2 and by 13.40% for Frame 3. This confirms the reduction occurred in the MRID value of the frames. The RRDR significantly improved by adding the external SMA bars. The RRDR reduced from 1.99% for the steel RC frame to 0.93% and 0.62% for frames 2 and 3 respectively. These values correspond to percents of change equal to 53.49% and 68.63% for Frames 2 and 3, respectively.

These drift results in addition to the previously introduced damage schemes show that retrofitting an existing RC frame by adding external SMA bars at the right locations can lead to: (i) lower level of damage; (ii) small reduction in the MID and MRDR values (10%-15%); (iii) significant (50%-70%) reduction in the residual deformations represented by MRID and RRDR; and (iv) tolerating higher intensity earthquakes.

9 CONCLUSIONS

This paper investigates the applicability of using external SMA bars to enhance the seismic performance of steel RC frames. A six-storey steel RC frame building is used as a reference for this study. The frame is assumed to be located in high seismic zone and is subjected to five different scaled earthquake records. After determining the collapse intensity for each record, the analysis is performed again for other two retrofitted frames. The two frames are retrofitted using the proposed retrofitting technique. The first frame is retrofitted at its first floor, while the second frame is retrofitted at the first and fourth floors.

The performance of the three frames is compared based on the: (i) maximum drifts represented by MID and MRDR; and (ii) residual drifts represented by MRID and RRDR. The retrofitted frames showed lower level of damage at failure and higher tolerated earthquake intensities. The suggested retrofitting technique reduced the maximum drifts of the frame by 10% to 15%, and reduced the residual drifts by 50% to 70%.

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