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Performance Assessment of Hybrid Steel Frames under Near-field Seismic Excitations

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Abstract

Assessment of the seismic performance of steel structures is topical research for a variety of earthquakes. Moment-resisting rigid steel frames are generally designed and used for high seismic zones. However, the famous Northridge in 1994 and Kobe in 1995 earthquakes exposed the shortcomings of moment frames. During these events, the beam-column connections of rigid moment frames were severely damaged. Since then, an alternative of welded connections called bolted or semi-rigid connections is considered for designing or retrofitting of steel moment frames. From the last few years, the semi-rigid connections combined with rigid connections, termed as hybrid or dual frames have become widely popular for earthquake designers and engineers due to enhanced ductility and reduced cost of construction. Earlier research work was focused on far-field (FF) earthquakes, whereas, the near-field (NF) earthquakes are crucial for civil engineering structures. In this paper, an extensive numerical study is carried on rigid and hybrid steel moment frames for NF and FF earthquakes. For this purpose, a ten-story rigid steel frame is analyzed and designed for seismic requirements as per Indian Standards. The rigid connections of frames are replaced by semi-rigid connections with a moderate degree of semi-rigidity. The six different patterns (locations of semi-rigid connections) of hybrid frames are considered here to compare the seismic performance of hybrid frames under near field earthquakes. The nonlinear response-history analyses are executed using the SAP2000 software at two scaled PGAs defined as low (i.e., 0.2g) and high (0.5g) level. An ensemble of three time-histories, each for both types of earthquakes are considered for the numerical simulation. Response quantities of interest, namely, the maximum value of base shear, story displacement, inter-story drift ratio, the total number of plastic hinges, and the square root of the sum of squares of maximum plastic hinge rotations are considered for the decision of a most appropriate pattern for hybrid frames. The results of the numerical study indicate that the response behavior for the NF earthquakes is distinctly different both in nature and magnitude. It is observed that the seismic demands under the NF earthquakes are substantially more as compared to those obtained for FF earthquakes for all cases of hybrid frames. Further, it is also found that the pattern and number of semi-rigid connections in the hybrid frame have a vital role in seismic performance.

Keywords: Near-field, Far-field, Hybrid, Semi-rigid connection, Seismic performance, Hybrid Frames

1. Introduction

The steel structures are generally preferred over reinforced concrete structure nowadays for industrial and multi-story residential and commercial buildings. The construction and fabrication costs of these frames are comparatively more as compared to the other civil engineering construction practices. However, due to high ductility and strength, the welded steel moment-frames are widely accepted by researchers and engineers from the last four decades under high seismic zones. After 2001, the Bhuj earthquake in India, the awareness towards the seismic-resistant design of structures is substantially increased.

During the 1994 Northridge and 1995 Kobe earthquakes, several welded moment-frames were undergone brittle failure of the beam to column connections. The main reason for the shortcomings was the stress concentration and ductility in the welded zone of connections [1]. These events diverted the attention of researchers towards alternative technology and the use of semi-rigid (SR) or bolted connections were preferred over welded frames. Several researchers found that the efficacy of steel frames was increased by using the semi-rigid connections (SR) in place of rigid connections. Various studies showed the improved performance of semi-rigid frames in the form of energy dissipation under severe earthquakes with different degrees of semi-rigidity [2-5]. Seismic performances of SR frames were examined experimentally and analytically by various researchers and revealed that SR connections have good ductility and the ability to dissipate a large amount of seismic energy without failing [6-8]. Díaz et al. [9] presented a state-of-the-art review paper on the behavior and categorization of SR connections based on their moment-rotation (M-θ) curve. The most preferred SR connectionsmodels are the Frye-Morris polynomial model, Kish-Chen power model, Bjorhovde model [10-12].

Most of the research studies and standards consider only the far-field earthquakes for performance evaluation. The research work under near-field earthquakes is meager for SR

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frames [3, 13]. Recently, Sharma et al. [14] carried out a comprehensive behavior study of SR frames subjected to near-field earthquakes and highlighted the efficacy of SR frames as compared to rigid frames.

On the other side, the complete replacement of rigid connections with SR connections increased the top-floor displacements and flexibility of steel frames which increase the susceptibility to damage due to pounding effects in the current scenario of closely spaced buildings under severe shaking. As a consequence, most of the design standards eliminated the use of semi-rigid or partially restrained connections for high seismic zones. Therefore, the concept of dual or hybrid frames in which partial replacement of rigid connections with SR connections is carried out become popular nowadays. In the hybrid frames, the rigid connections provide the required lateral stiffness and the lower down the seismic energy level to maintain the higher lateral displacement under the limit. On the other side, the SR connections fulfill the ductility requirement. Dubina et al. [15] suggested that stiffener members can be eliminated or reduced in the hybrid frames, which results in lower construction costs. Since SR connections are bolted connections so it can be repaired easily after damage induced due to any severe shaking [16]. Earlier, few researchers investigated the seismic performance of hybrid frames with a reduced number of SR connections with the rigid connections [17-19]. Abolmaali et al. [17] presented the concept of hybrid frames using in the 9- and 20-story SAC benchmark frames and identified the energy dissipation capabilities. Several different patterns and locations are identified for SR connections for improved performance, especially for those 9- and 20-story SAC frames. Feizi et al. [18] studied the behavior of steel frames with a combination of rigid and SR connections under dynamic loadings and found that hybrid frames performed relatively better in terms of base shear and drift values. Recently, Bayat et al. [19] suggested the different patterns for 10, 15, and 20-story steel frames and compared the base shear, story drift, and roof accelerations with the responses obtained from respective rigid frames. These studies focused only on the far-field earthquakes.

Various studies focused on the SR frames only and very less attention was paid to the seismic performance of hybrid steel frames. The present study investigated the seismic performance of the ten-story with a three-bay symmetric hybrid steel frame under the near-field earthquakes. The study also intends to identify the appropriate pattern and location of SR connections. An ensemble of three ground motion time histories, each for far- and near-field earthquakes are scaled at two PGA levels (denoting low and high level). The response quantities of interest include the maximum value of inter-story drift ratio (MIDR), base shear, story displacements. the total number of plastic hinges and SRSS of maximum plastic hinge rotations. The responses are compared for the nature of earthquakes, pattern type, and a number of SR connections.

2. Methodology

The performance of hybrid or dual steel frames is basically dependent on the number of semi-rigid (SR) connections and their properties. The distribution of SR connections also plays a significant role in the seismic performance of hybrid steel frames. The properties of SR connections are governed by the moment-rotation curve. In this section, the detailed modeling of SR connections and its implication in the application software SAP2000 is explained [20]. The different distribution patterns used in the study with their dynamic properties are also discussed here. The numerical simulation is carried out using the nonlinear response history analysis (NRHA) at two scaled PGA levels for a 10-story steel frame.

2.1 Analytical Approach

A 10-story 3-bay symmetric rigid steel special moment frame (SMF) frame is analyzed and designed as per the Indian Standard requirements. The nonlinear response-history analysis (NRHA) is executed to assess the seismic performance of rigid and hybrid steel frames. The flexural beam member is modeled like an elastic member with default moment type (M3) plastic hinges at the ends and default P-M3 type hinges are employed in column ends which considers the interaction of axial force with bending moments. The default hinge-properties are described in Fig. 1 as per the ASCE-41 [21] acceptance criterion. Three performance levels are defined in the curve, immediate occupancy (IO), life safety (LS), and collapse prevention (CP) and the values are obtained from Table 9.6 of ASCE-41. The secondary P-delta effects are considered to carry the geometric nonlinearity. Therefore, in this study, three types of nonlinearity, namely, the connection nonlinearity, material nonlinearity (in form of concentrated default flexural hinges), and geometric nonlinearity are taken. For the NRHA in SAP2000, the Hilber-Hughes-Taylor direct integration scheme is used for numerical simulation with default values. The Rayleigh proportional damping is considered with the 5% damping for the first and second modes of vibration.

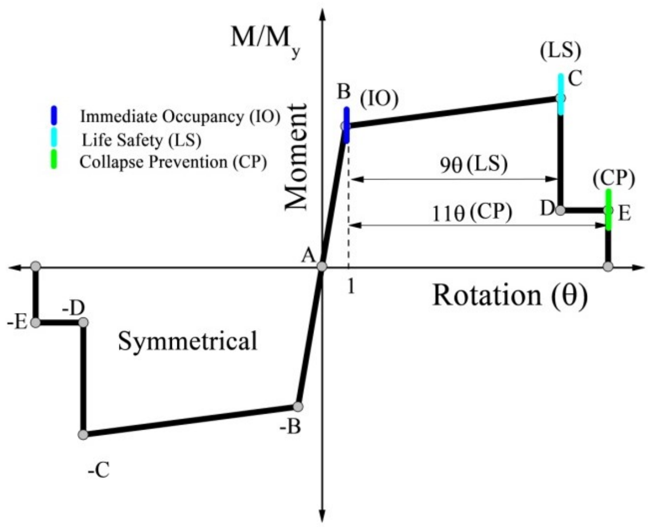

Fig. 1 Backbone curve for plastic hinges according to ASCE 41-17 guidelines

2.2 Properties of SR connection and modeling methodology

Various codes of practice explained the properties of SR connections are defined by the three parameters, namely, stiffness parameter (**k**), flexural strength parameter (γ), and the ductility of the frame (**μ**) [22-24]. The present study is based on the parameters defined in AISC 360 and seismic strengthening requirements suggested by AISC 341. The degree of semi-rigidity is defined by stiffness and strength parameters. For the present study, the SR connections are designated by a moderate degree of semi-rigidity. The moment-rotation curve for SR connections is shown in Fig 2. According to the AISC 341 guidelines, the ratio of the yield moment ($\mathbf{M_{yc}}$) capacity to the plastic moment capacity of connections ($\mathbf{M_{pc}}$) in the generic model is chosen as 2/3. The flexural strength or ultimate moment capacity of connections at the column ends should be a minimum 80% of the connecting beam plastic moment capacity ($\mathbf{M_{pb}}$) to satisfy the story drift limit (minimum 0.04 rad) of connection as per AISC 341-16. The moderate degree of semi-rigidity in connections are defined by two dimensionless parameters (**k** = 10 and **γ** =1.5) and the connection ductility. For SR connections, the ductility of connections should not be less than $\theta_u \geq 0.04$ rad. The parameters are taken as follows:

$$k = K_i/\,(EI_{beam})/L_{beam}) \tag{1}$$

and $$\gamma = M_{pc}/M_{pb} \tag{2}$$

Where $\mathbf{K_i}$= Initial Connection Stiffness;
$\mathbf{EI_{beam}/L_{beam}}$ = Stiffness of connected beam members

The SR connections are modeled in SAP2000 using the zero-length two jointed multi-linear plastic links (MLP) with rotational nonlinearity in default R3 direction. The material nonlinearity in the structure is modeled like a concentrated flexural plastic hinge as per default ASCE 41-17 [21] recommendations, and geometric nonlinearity is incorporating through secondary P-Δ consideration. The kinematic hysteresis behavior of MLP links for energy dissipation in cyclic loadings is shown in Fig. 2.

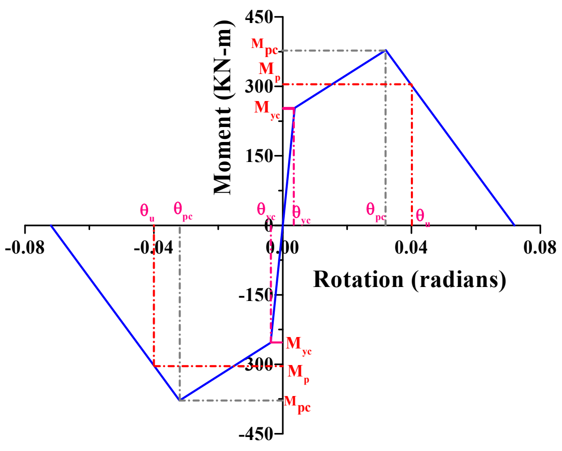

Fig. 2 Moment-Rotation Curve for SR connection for 10-story SR connection with a moderate degree of semi-rigidity (k=10; γ=1.5)

2.3 Classification of distribution patterns for hybrid frames

The location or arrangement of SR connection in the hybrid frames follows some specific patterns as used in previous studies [18, 19, 25]. A new pattern similar to 'Stoup' or 'Kalash' shape is suggested in the present study. The dynamic properties and classification of six different patterns for hybrid frames are shown in Fig. 3 and Table 1. The number of SR connections are varied for each pattern.

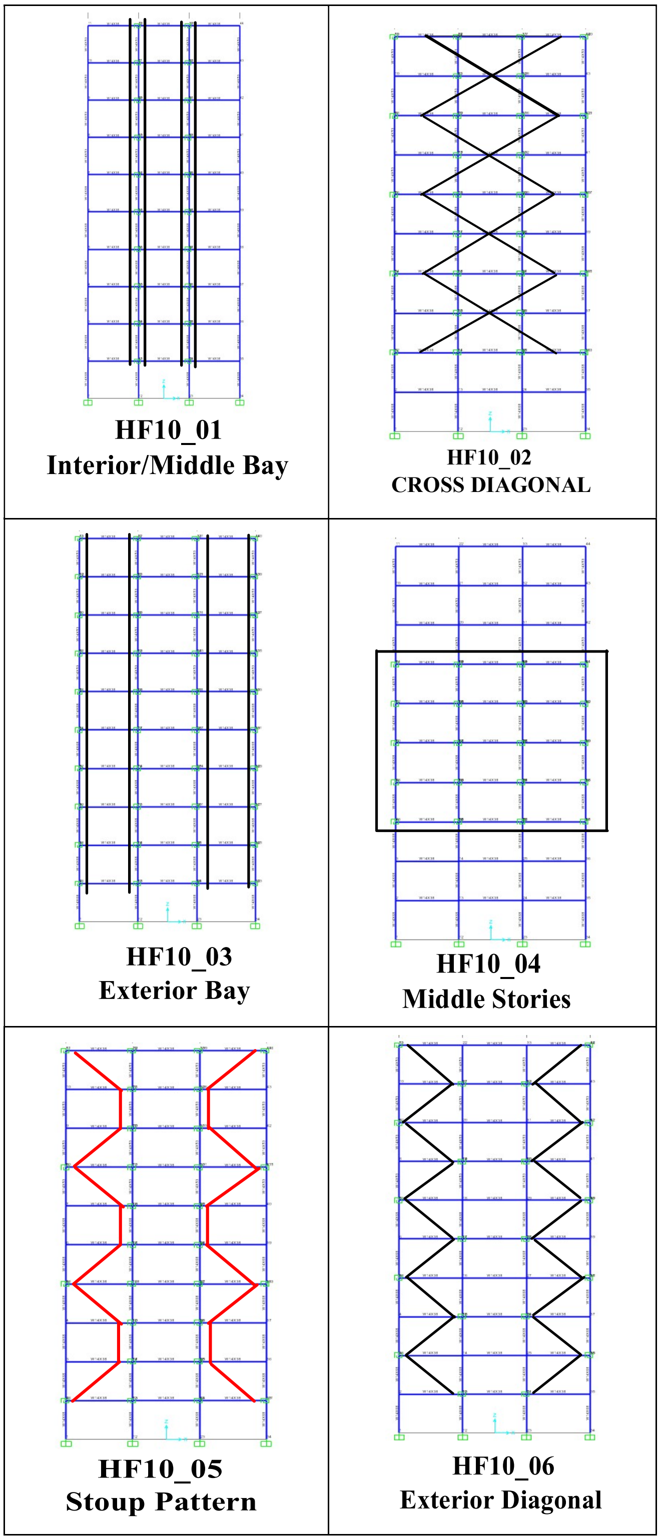

Fig. 3 Different pattern for 10-story Hybrid pattern

Table 1- Classification of the hybrid frames with different patterns for semi-rigid connection

Sr. No.	Pattern Name	N$	Natural period of time (sec)		
			T_1	T_2	T_3
1	HF10_01 (Interior/Middle Bay)	20	1.907	0.623	0.35
2	HF10_02 (Cross Diagonal)	28	1.94	0.633	0.356
3	HF10_03 (Exterior/ Outer Bay)	40	2.01	0.654	0.367
4	HF10_04 (Middle Stories 3-7)	30	2.014	0.636	0.357
5	HF10_05 (Stoup)	28	1.938	0.633	0.356
6	HF10_06 (Exterior Diagonal)	20	1.919	0.627	0.353
7	RFR10 (Rigid Frame)	0	1.823	0.687	0.338

$ N= Number of SR connections

3. Numerical Study

For the numerical simulation, a ten-story frame with rigid and semi-rigid connections designed by Sharma et al. [26] are considered. The 10-story frame has an identical height of 3.2 m each with three bays of 5 m each in both directions. The building comprises of special moment resisting frames with rigid beam to column connections. The sections are selected to ensure the capacity design concept, i.e., the stiffnesses of columns are 1.2 times the connected beam stiffness (strong column-weak beam; SCWB). The frames are subjected to gravity load resulted from 150 mm thick concrete slab along with floor finish and 225 mm thick partition wall load. The effective gravity load consists of 20KN/m as dead load, 15 KN/m as roof load, and 4 KN/m as live load, uniformly distributed over beams. Table 2 shows the effective gravity loading on beams and section detail used for frames. The SMFs are designed for seismic strengthening as per Indian standards IS-800 [27], IS 1893-Part-1 [28], and IS 875 [29]. The seismic design parameters considered for design are zone factor (Z=0.36, Zone V), soil type (medium soil), importance factor (I=1 for high rise commercial building), and response reduction factor for frame type (for SMRF, R=5). An ensemble of three ground motion time-histories each for the far-field (FF) and near-field (NF) earthquake records are used for study and the characteristics of time-histories are shown in Table 3.

Table 2: Gravity loading and Section Detailing Of 10-Story Steel Moment Resisting Frame

Gravity Loading Detail				
Sr. No	Floor	Height (m)	Dead Load (KN/m)	Live load (KN/m)
1	1^{st}-9^{th}	3.2 each	20	4
2	10^{th}	3.2 each	15	4
Section Detail				
Sr. No	Floor	Bay Width	Beam	Column
1	1^{st}-6^{th}	5 m	W 14X38	W 14X53
2	7^{th}-10^{th}	5 m	W 14X38	W 14X68

Table 3: Characteristics of far- and near-field records

No	Event Year	Ground Motion-Component	M_w^*	PGA (g)	PGV (cm/s)	PGD (cm)
Far Field Earthquake (FF)						
1	1995	Kobe-Nishi-000	6.9	0.51	37.28	9.53
2	1992	Landers-TR	7.3	0.42	42.35	13.84
3	1978	Tabas-Ferdows-L	7.4	0.093	5.4	2.24
Near-Field Earthquakes (NF)						
1	1992	Erzincan-EW	6.7	0.5	64.32	21.91
2	1994	Northridge-Sylmar-018	6.7	0.83	117.5	34.45
3	1979	Imperial Valley-270	6.53	0.35	75.58	57.15

***Mw: Magnitude**

Earthquake time-histories measured within 20 km from the fault rupture line are designated as near-field records and the records with the closest distance more than 20 km are denoted far-field records. For the present study, the earthquake records are selected from the FEMA P695 [30] report. In the near field region, the earthquakes at particular sites are greatly influenced by the fault rupture mechanism, slip direction relative to the rupture, and permanent ground displacement at the site relative to the residual tectonic displacement [31]. Further, the smoothened response spectrum for far-field and near-field earthquakes are also presented here to differentiate the nature of two earthquakes in Fig. 4.

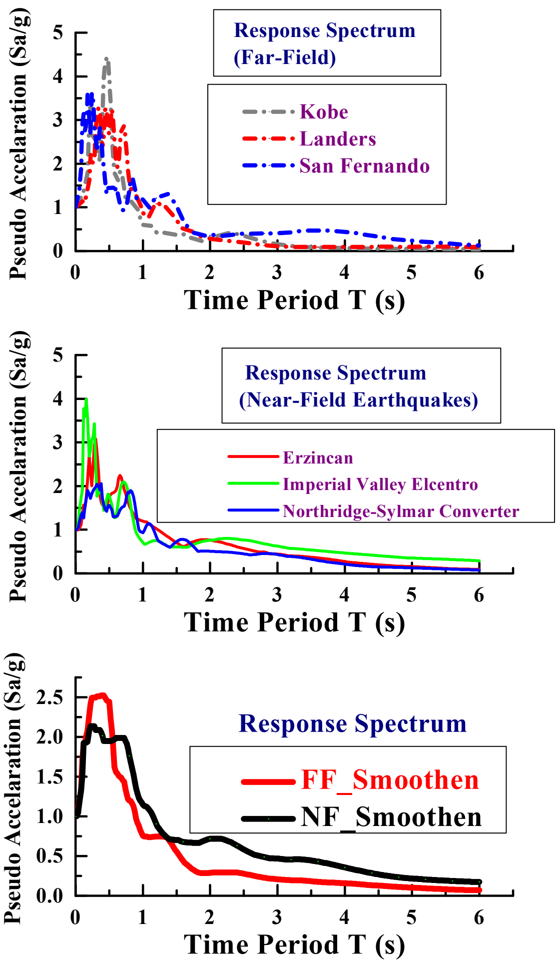

Fig. 4. Response Spectrum for far- and near-field earthquakes

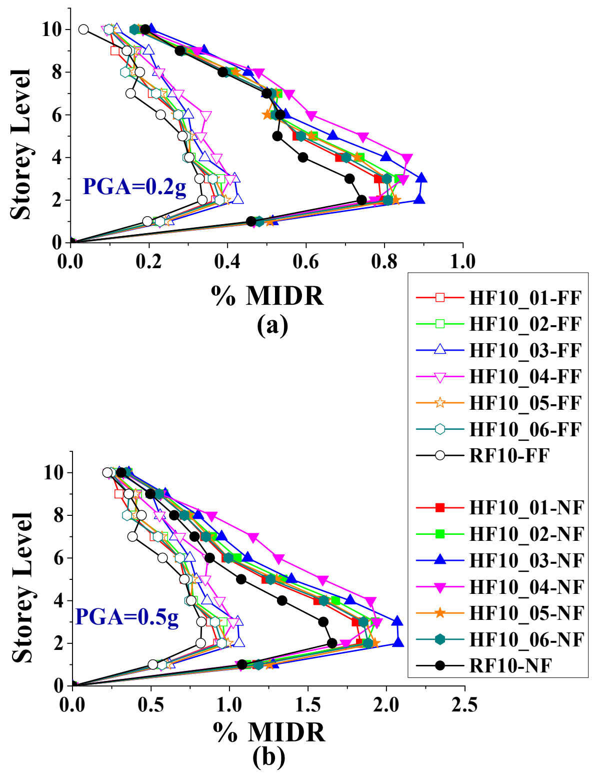

Fig. 5 Variations of MIDR along with height in hybrid frames

4. Results and Discussion

For the two different types of earthquakes, namely, far-field and near-field, the seismic demand parameters are represented in the mean and maximum values of responses obtained from the three ground motion time-histories. In each suite of earthquakes, the records are scaled at two peak ground acceleration (PGA) levels. For exemplification, the plots of maximum values of inter-story drift ratio and story displacement along the story level are represented in Fig. 5 and 6 for the six different hybrid frames and rigid frame. It is noticed that each figure consists of 14 plots. Seven plots are generated for far-field earthquakes (symbols without fill) and others are for near-field earthquakes (with filled symbols). The other response parameters for comparison of hybrid frames with different patterns are maximum values of base shear, the total number of plastic hinges, and the square root of the sum of squares (SRSS) of maximum plastic hinge rotations, represented in tabular form. The responses are discussed considering the number of SR connection, types of pattern, PGA level, and variety of earthquakes.

4.1 Variation of maximum values of inter-story drift ratio (MIDR) for hybrid frames

The variation of MIDR along with the story level for six hybrid frames as compared to the rigid frame for FF and NF earthquakes at two PGA levels (0.2g and 0.5g) are represented in Fig. 5. The MIDR responses along the story level follow a similar trend with the rise in PGA levels and

Table 4: Mean values of MIDR for different hybrid frames under far- and near-field earthquakes

Frame ID	Mean Value of maximum IDR			
	FF	NF	FF	NF
	0.2g		0.5g	
HF10_01	0.370	0.790	0.925	1.834
HF10_02	0.387	0.837	0.968	1.929
HF10_03	0.426	0.894	1.062	2.074
HF10_04	0.407	0.857	1.024	1.939
HF10_05	0.395	0.829	0.990	1.927
HF10_06	0.380	0.809	0.952	1.883
RF10	**0.336**	**0.742**	**0.821**	**1.654**

differ with the type of pattern. Since the flexibility of hybrid frames is dependent on the number of SR connections, the trend for MIDR values varies with the pattern type. For all cases, the MIDR values along the story level are observed least in the case of the interior or middle bay (HF10_01) pattern. The MIDR responses are nearly the same but slightly on the higher side in the hybrid frame with an exterior bay (HF10_06) pattern. It is observed that the MIDR values are increased with an increase in the number of SR connections (20 in the case of HF10_01 and HF10_06 to 40 for HF10_03). The maximum values of MIDR in all cases are observed in the lower stories (mainly at the second or third story) level.

Further, It is observed that the near-field earthquakes imposed more demand as compared to FF earthquakes. It is noticed that at the same PGA level, there is a significant difference that occurred in the responses obtained in NF earthquakes as compared to those obtained in FF earthquakes. The differences vary up to two to three times under the NF earthquakes for MIDR values. The mean values of MIDR are represented in Table 4. The MIDR is the most promising criteria for seismic performance of frames, and the hybrid frames fulfill the effectiveness under high PGA levels of earthquake. The hybrid frames perform considerably well in NF earthquakes as the maximum values of mean MIDR is nearly 2% which is considered under the permissible limit (for collapse prevention ‘CP’ state, permissible values should be less than 4%).

4.2 Variation of maximum values of story displacement

Fig. 6 shows the variations of story displacements with story level for hybrid frames with different patterns as compared with the rigid frame at two PGA levels for two different types of earthquakes. It is noticed that the story displacement increases with an increase in the number of SR connections, maximum in the HF10_04 hybrid frame (40 SR connections). The pattern of SR connections also significantly affect variation in story displacement. It is observed that the hybrid frame HF10_04 with 30 SR connections represents nearly the same story displacement with HF10_03 with 40 SR connections.

Table 5- Mean values of Story Displacement for different hybrid frames under far- and near-field earthquakes

Frame ID	Mean value of Top story displacement (mm)			
	FF	NF	FF	NF
	0.2g		0.5g	
HF10_01	76.76	166.81	191.28	231.64
HF10_02	81.51	173.03	203.63	243.57
HF10_03	91.11	186.11	228.59	264.71
HF10_04	90.33	187.11	225.69	258.37
HF10_05	81.3	172.62	203.22	243.16
HF10_06	78.17	168.4	194.94	235.24
RF10	**69.91**	**149.27**	179.24	212.52

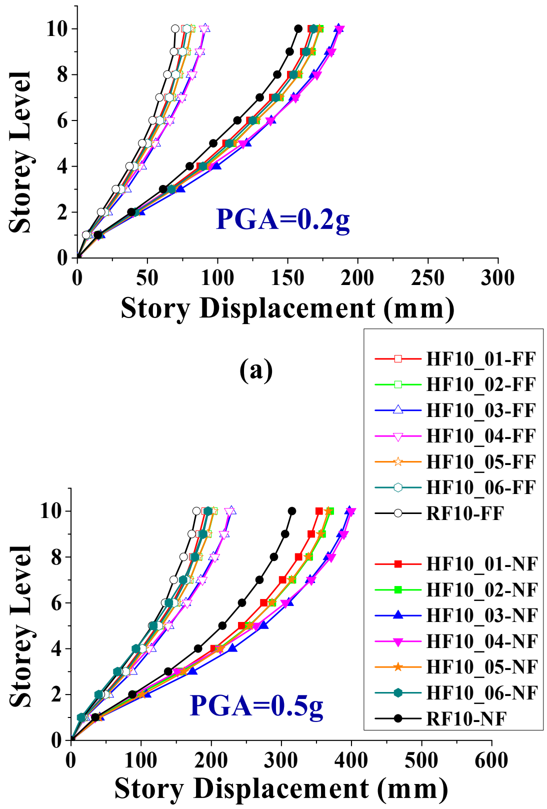

Fig. 6 Variation of story displacement with story level for hybrid frames

The nature of earthquake (i.e., NF or FF) affects similar to MIDR response that the responses are 2 to 3 times more for NF earthquakes as compared to those responses obtained under FF earthquakes. The responses increase with a rise in PGA levels for both types of earthquakes and the trend of variation is similar, irrespective of earthquakes.

Further, Table 5 represents the maximum and mean values of story displacements for hybrid frames. The table shows that the pattern with interior bay and external diagonal performs well as compared to other patterns. On this basis, the HF10_01 is suggested as the most appropriate pattern.

Table 6- Mean values of maximum base shear (KN) for different hybrid frames under far- and near-field earthquakes

Frame ID	Mean value of Maximum Base Shear (KN)			
	FF	NF	FF	NF
	0.2g		0.5g	
HF10_01	213.71	453.54	533.82	889.44
HF10_02	217.79	454.29	543.73	879.87
HF10_03	218.84	447.25	540.84	832.31
HF10_04	225.89	462.37	561.17	877.4
HF10_05	218.62	455.11	544.89	869.37
HF10_06	214.02	453.27	534.98	883.28

4.3 Variation of maximum values of base shear

Table 6 shows the variation of mean values of the maximum base shear at two PGA levels for hybrid steel frames for FF and NF earthquakes. The mean values are the average of maximum base shear responses obtained from three different time-histories, each for FF and NF. It is noticed that minimum base shear is noticed in the pattern with SR connections in the interior or middle bay for both conditions (i.e., maximum and mean values) and suggested as the most appropriate pattern. The pattern with exterior diagonal (HF10_06) also holds good.
It is also observed that the base shear is significantly more for near-field earthquakes and increases with a rise in PGA levels for both types of earthquakes. The differences in base shear for far-field earthquakes are more than twice for all hybrid frames. Whereas, the rise in base shear is slightly less than double for NF earthquakes for all hybrid frames

4.4 Variation of the total number of plastic hinges and SRSS of the maximum plastic hinge rotations hybrid steel frames

Table 7 shows the formation of the total number of plastic hinges and SRSS of maximum plastic hinge rotations under FF and NF earthquakes at a high PGA level for the rigid and hybrid frames. The earlier research studies showed that a significant reduction of the formation of plastic hinges observed in the case of frames with SR connections as compared to the rigid frames. Table 7 shows that less number of plastic hinges are formed under the FF earthquakes and a considerable rise in plastic hinges are noticed for the NF earthquakes. There is no reduction observed in the total number of plastic hinges for hybrid frames as compared to the rigid frame under FF earthquakes.

On the other side, the less number of plastic hinges formed in the hybrid frames as compared to the rigid frame under NF earthquakes. The reduction is more with the rise in the number of SR connections (HF10_03 and HF10_04) used in different patterns. It is interesting to note that the HF10_04 pattern consists of 30 SR connections but the hinge formation is more than HF10_03 (with 40 SR connections). Therefore, the pattern also considerably affects the hinge formation.

Table 7: Total Number of Plastic Hinges and SRSS of maximum plastic hinge rotations at the PGA level of 0.5g

Frame model	FF	NF	FF	NF
	Total Hinges		SRSS (radian X 10^{-3})	
HF10_01	6	35	1.58	36.6
HF10_02	5	36	1.79	35.23
HF10_03	9	27	2.66	33.17
HF10_04	4	22	2.73	31.8
HF10_05	6	31	2.33	35.92
HF10_06	3	37	0.49	33.33
RF10	2	45	0.18	32.59

The SRSS values of maximum hinge rotations under NF earthquakes are nearly the same for the HF10_04 pattern as compared to the rigid frame. Since the maximum inter-story drift ratio is noticed in middle and lower stories of the rigid frame; the formation of plastic hinges concentrates at lower and middle stories. Therefore, the formation of the number of hinges can be reduced by providing SR connections and it is observed in pattern with SR connection in the middle stories (HF10_04). Therefore, the present table simply compares the number of hinges and SRSS values in hybrid frames.

5. Conclusions

The performance of high-rise ten-story moment-resisting steel rigid and hybrid steel frames are evaluated at the two scaled peak ground acceleration (PGA) levels (denoting the 0.2g as low and 0.5g as high) for an ensemble of three time-histories, each for near- and far-field earthquakes. For the numerical simulation, six different locations/patterns of semi-rigid connections are considered to define the hybrid frame. The nonlinear response-history analyses at two PGA levels for rigid and hybrid frames are performed to extract the wide range of seismic responses. The seismic demand parameters include the maximum values of inter-story drift ratio (MIDR), story displacement, base shear, the total number of plastic hinges, and the SRSS values of maximum plastic hinge rotations. The most appropriate patterns for hybrid frames based on response quantities are suggested for far- and near-field earthquakes. The major conclusion from the numerical study are as follows:

1. The near-field earthquakes impose considerably higher seismic demands as compared to far-field earthquakes. Therefore, all the response quantities are significantly more in the NF earthquakes than those obtained under FF earthquakes.
2. The distribution/locations of SR connections substantially affect the performance of hybrid frames.
3. The hybrid frames with more number of SR connections, generally, have generated more values of MIDR and story displacement due to an increase in flexibility.
4. The maximum MIDR is observed at the bottom (at second and third story level) story levels for both PGA levels.
5. Less number of plastic hinges are formed in the hybrid frames as compared to rigid frames under the NF earthquakes. In general, the number of hinges reduces with an increase in the number of SR connections. This is due to the availability of additional energy dissipation source in SR connection. However, in some cases like in HF10_04 (30 SR connections), less number of hinges are formed irrespective of more number of SR connections (which means HF10_03 have 40 SR connections). Therefore, the pattern plays an important role in the formation of plastic hinges.
6. The trend of variations in the mean values of MIDR and story displacement along story level does not vary substantially with an increase in PGA levels. This might be due to the averaging effect of responses. But the values are more in NF earthquakes for all cases.
7. The pattern with the SR connections in the interior or middle bays is the most appropriate pattern (HF10_01) as compared to other cases. The newly suggested 'Stoup Pattern' also performs well as compared to the cross diagonal (HF10_02) and exterior bay (HF10_03) pattern.

Disclosures

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