Steel and Composite Structures, *Vol. 19, No. 6 (2015) 1449-1466*
DOI: http://dx.doi.org/10.12989/scs.2015.19.6.1449

Response modification factor of mixed structures

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(*Received October 22, 2014, Revised June 11, 2015, Accepted June 17, 2015*)

Abstract. Mixed structures consist of two parts: a lower part and an upper part. The lower part is usually made of concrete while the upper part is made of steel. Analyzing these structures is complicated and code-based design of them has many associated problems. In this research, the seismic behavior of mixed structures which have reinforced concrete frames and shear walls in their lower storeys and steel frames with bracing in their upper storeys were studied. For this purpose, seventeen structures in three groups of 5, 9 and 15 storey structures with different numbers of concrete and steel storeys were designed. Static pushover analysis, linear dynamic analysis and incremental dynamic analysis (IDA) using 15 earthquake records were performed by OpenSees software. Seismic parameters such as period, response modification factor and ductility factor were then obtained for the mixed (hybrid) structures using more than 4600 nonlinear dynamic analysis and used in the regression analysis for achieving proper formula. Finally, some formulas, effective in designing such structures, are presented for the mentioned parameters. According to the results obtained from this research, the response modification factor values of mixed structures are lower compared to those of steel or concrete ones with the same heights. This fact might be due to the irregularities of stiffness, mass, etc., at different heights of the structure. It should be mentioned that for the first time, the performance and seismic response of such structures were studied against real earthquake accelerations using nonlinear dynamic analysis, andresponse modification factor was obtained by IDA.

Keywords: mixed structure; response modification factor; overstrength factor; ductility factor; transition storey

1. Introduction

Seismic codes usually use linear analysis of structure but rely on nonlinear behavior in the structural design. Seismic codes consider a reduction factor in designing the loads in order to cause the structure to enter into the nonlinear behavior region and then use the advantages of its energy dissipation. Actual seismic forces are reduced by the mentioned reduction factor, usually called response modification factor, to obtain design forces**.** In different codes, response modification factor is presented for any structural system based on the ductility (R_μ) and overstrength (R) of the structures. The concept of response modification factor was presented for the first time based on the ductility, overstrength and indeterminacy of structures for calculating the least design base

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http://www.techno-press.org/?journal=scs&subpage=8 ISSN: 1229-9367 (Print), 1598-6233 (Online)

Fig. 1 A mixed structure (Tehran, Iran)

shear; it was presented in ATC-3-06 and modified in ATC-19 and ATC-34. Seismic codes provide no seismic provisions, particularly response modification factor and period, for mixed structures; i.e., only a few suggestions have been mentioned in ASCE/SEI 7-10 and Iranian National Building Regulation, part 6.

Mixed structures are structures made of different types of materials at their different storeys. The lower parts of these structures are usually made of concrete while their upper parts are made of steel. Such structures have been widely used in multi storey buildings. Constructing a steel structure on the existing concrete building generates a mixed structure. This structural system has non-uniform distribution of stiffness, mass, material and damping in the vertical direction. Fig. 1 is an example of a mixed structure.

The various studies which have been conducted based on hybrid or mixed structures are of high varieties. They are mostly related to:

- mixed structures or mixing structures in a building plan (Lu *et al*. 2011);
- the general behavior of structures, other than ordinary buildings, with different materials along its height such as general dynamic behavior of columns in cable bridges, Abdel Raheem (Abdel Raheem 2011);
- the dynamic specifications of structures such as damping matrix (Papageorgiou *et al*. 2010, 2011 and Sivandi-Pour *et al*. 2014);
- a certain case study (Lu *et al*. 2009) and (Aste *et al*. 2003).

Several researchers have focused on the irregularity along the height of structures (Chintanapakdee and Chopra 2004 and Das and Nau 2003).

In all these studies, the structural irregularity along height is mainly related to the changing the structural section along it and not to a change of lateral loading system, and more importantly, not to the kind of material used at different heights of the buildings. No significant investigation has been conducted on the seismic behavior of mixed structures in terms of height, particularly time history and nonlinear dynamic analyses. It means that this area suffers from information and results shortages.

Up till now, no comprehensive research has been conducted on the performance of these structures and their seismic responses under a real earthquake. Mixed structures are commonly composed of reinforced concrete frames with shear walls in their lower storeys and steel frames with bracing in the upper storeys (Fanaie and Shamloo 2012). This paper studied the seismic behavior of mixed structures with one transition storey. The transition storey, located in the transition level, is a composite (steel-concrete) storey with composite columns, shear walls and steel bracing.

2. Response modification factor

According to the nonlinear behavior of structures, stress and base shear force of structures under an earthquake are lower than those in the elastic analysis. The codes usually consider a series of reduction factors for design forces, taking advantage of energy dissipation of the structure in the nonlinear area without collapse. Response modification factor is related to the energy dissipation capacity of structures by non-linear deformation without collapse.

Response modification factor is calculated based on Uang's method (1991). Generally, the nonlinear behavior of a structure is idealized by a bilinear elastic-perfectly plastic curve and shown in Fig. 2. In this bilinear model, V_y and Δ_y are yield strength and yield displacement of the structure, respectively. Assuming a linear behavior of the structure during earthquakes, maximum base shear (V_e) decreases to V_y because of its ductility and nonlinear behavior (Uang 1991).

Ductility reduction factor is defined as follows

$$R_\mu = V_e / V_y \tag{1}$$

Overstrength factor is calculated by dividing the idealized yield strength (V_y) by the first significant yield strength (V_s)

$$R_s = V_y / V_s \tag{2}$$

Allowable stress factor is the ratio of the first significant yield strength to the allowable stress design strength.

$$Y = V_s / V_w \tag{3}$$

According to the design codes, the first significant yield strength is reduced to the allowable design strength in the allowable stress design method by this factor (Y) (Uang 1991).

The three components mentioned above are used in calculating the response modification factor (R) and expressed as follows

$$R = R_\mu \times R_s \times Y \tag{4}$$

The allowable stress factor (Y) becomes unity when the structure is designed by ultimate state method and the response modification factor is reduced to

$$R = R_\mu \times R_s \tag{5}$$

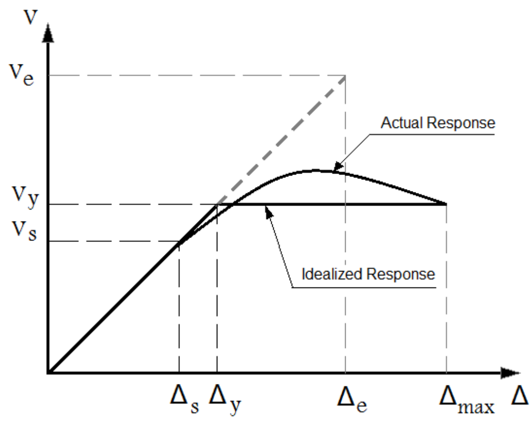


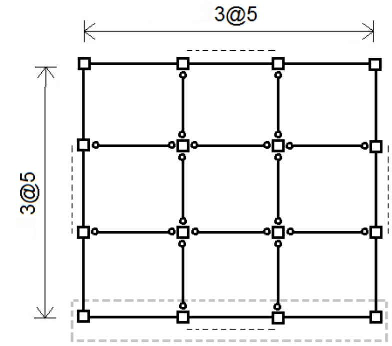
Fig. 2 General response of structure

3. Designing the modeled structures

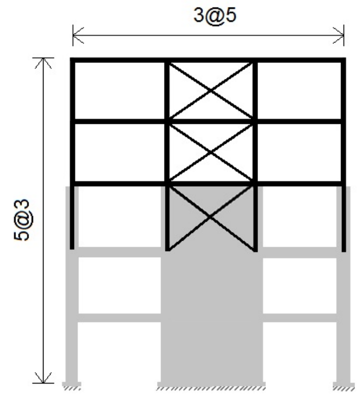
Seventeen structures of 5, 9 and 15 storeys were designed and summarized in Table 1 for the purpose of this study. The structures have different numbers of steel and concrete storeys.

Table 1 Modeled structures

Number of stories	Structure name	Number of steel stories	Number of transition stories	Number of concrete stories
5	0S0T5C	0	0	5
	1S1T3C	1	1	3
	2S1T2C	2	1	2
	3S1T1C	3	1	1
	5S0T0C	5	0	0
9	0S0T9C	0	0	9
	2S1T6C	2	1	6
	4S1T4C	4	1	4
	6S1T2C	6	1	2
	9S0T0C	9	0	0
15	0S0T15C	0	0	15
	3S1T11C	3	1	11
	5S1T9C	5	1	9
	7S1T7C	7	1	7
	9S1T5C	9	1	5
	11S1T3C	11	1	3
	15S0T0C	15	0	0



(a) Plan of the structure (unit: m)



(b) Configuration of the structure (unit: m)

Fig. 3 5 storey mixed structure

In this table, the names of structures have been abbreviated. For example, "2S1T2C" stands for a structure with two steel storeys (*S*), one transition storeys (*T*) and two concrete storeys (c). All mixed structures have one transition storey which is a composite (steel-concrete) storey with composite columns, shear walls and steel bracing. Fig. 3 shows the typical plane of all models**.** The storey height and the bay length are 3 m and 5 m, respectively for all structures. The position of the frame is extracted from three-dimensional structures which are shown in Fig. 3(a) with dotted.

Fig. 3(b) shows the configuration of the five storey structure. The dead and live loads are assumed to be 7 kN/m^2 and 2 kN/m^2, respectively. Ordinarily, the concrete storeys are considered along with the steel storeys for different applications such as store, car park, stockroom etc. in the mixed structures due to the advantages of concrete parts such as their fireproof specification. Therefore, the live loads of these storeys are considered differently from those of steel storeys. Here, the concrete storeys with live loads of 5 kN/m^2 were considered as store and car park. Table 2 shows the specifications of materials used in the designing and analysis of the structures.

According to the recommendation of the codes for mixed structures, the value of *R* (response modification factor) used in the design of the lower system should not be greater than that of the upper system. Two procedures, used in designing mixed structures are discussed here. If the conditions mentioned below are satisfied, both procedures can be used; otherwise, only the first one is applied in designing mixed structures.

Table 2 Specifications of materials

Concrete material C35		Steel material ST37	
Mass per unit volume	2.5 gr/cm^3	Mass per unit volume	7.848 gr/cm^3
Modulus elasticity of concrete	2.5e5 kg/cm^2	Modulus elasticity of steel	2.1e6 kg/cm^2
Compressive strength of concrete	350 kg/cm^2	Yield stress of steel	2400 kg/cm^2
Yield stress of longitudinal bars	4000 kg/cm^2	Ultimate stress of steel	3700 kg/cm^2
Yield stress of transverse bars	3000 kg/cm^2		

The conditions are:

(a) Both parts can separately be classified as regular structures.

(b) The average storey stiffness of the lower part is at least 10 times greater than that of upper part.

(c) The fundamental period of the entire structure is not greater than 1.1 times that of the upper part, while this part is considered as a separate structure with fixed base.

Procedure 1:

In this procedure, the seismic load is determined based on the lower *R* factor along the height of the structure. The empirical formula results in the fundamental period is used for both systems.

Procedure 2:

This procedure has two stages:

(a) The flexible upper part is designed as a separate structure with rigid supports based on the *R* factor corresponding to its structural system.

(b) The rigid lower part is designed as a separate structure, using its corresponding *R* factor. The reactions between the upper and lower parts are increased by the ratio of the *R* factor of the upper part to the *R* factor of the lower part and super-imposed to the loads acting on the lower portion.

The *R* factor of upper storeys should be equal to or more than that of lower storeys. Therefore, intermediate concrete moment resistant frame with intermediate reinforced concrete shear wall (R = 8) was used in the lower storeys while a dual system composed of special moment resistant frame and concentric bracing (R = 9) was used in the upper storeys. In Procedure 1, mixed structures should be designed based on the lower R. Therefore, the entire mixed structure is designed using response modification factor as 8 (R = 8).The equivalent static method was applied for all 5 storey structures as well as 9 and 15 storey regular structures. However, this method cannot be used for 9 and 15 storey mixed structures. Thus, spectral dynamic analysis was applied for seismic design of these irregular structures. All responses were finally scaled using the ratio of static base shear to dynamic base shear. Seismic lateral forces are distributed between the frames and bracings or shear walls based on their stiffnesses. Moreover, resisting frames should withstand 25 percent of the lateral load, independently.

4. Numerical simulation

2D frames of designed structures are modeled and analyzed in OpenSees software; an example is shown in Fig. 4. While all other connections are rigid in the upper structure, the braces are connected to the frame by hinge joint. The 0.001 imperfection of length is considered at the middle of these members in order to model the buckling of steel columns and bracings. Shear wall element is placed between two mid columns, Fig. 4.

Two rigid beams are modeled above and under the shear wall element using “rigid Link” elements. In the transition storey, steel brace is placed in the shear wall and therefore, it is prevented from buckling. The imperfection is not considered. In the transition storey, the shear wall is modeled as two elements and attached to the center of the bracing in its middle joint in order to model the interaction between the shear wall and the bracings. The transition storey

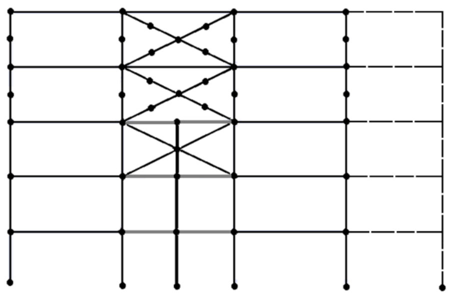


Fig. 4 The 2D frame of the structure modeled by OpenSees

columns are composite and consist of a steel box placed in a square section of concrete. Shan Su Zheng *et al*. (2011) and Kang *et al*. (2013) studied composite columns based on OpenSees program. These studies were used to simulate the SRC columns. The beam over composite columns is steel. Material model "Steel02", available on OpenSees, was used for steel elements. In order to consider the failure of steel material, minimum and maximum strain of steel02 material is defined using MiniMax material. The MinMax Material command is used to manage the Steel02 material. If the material strain of Steel02 rises above the Max-defined value, the material's stress falls to zero; also, when the strain falls below the Min-defined value, the material's stress falls to zero. So the Steel02 was assumed to have failed. Nonlinear beam-column element is adopted for all columns and X-bracing and displacement-based beam-column element for all beams (Mazzoni *et al*. 2007).

The elements were divided into 6 parts in their length in order to obtain more accurate results; effect of the weight of other frames was modeled with a dummy column. Large deformations as well as the effects of second order analysis were considered using corotational coordinate transformation. Corotational coordinate transformation is considered for dummy column, columns and bracing elements, and linear coordinate for beams "zero-length" and "eqalDof" are used in modeling of hinge connection (bracing to the steel frame). All the elements ofthe beams and columns are assigned as fiber sections. Material model "Concrete04" was used for concrete columns and beams. The sections of concrete elements are divided into confined and unconfined regions. Confined concrete model, proposed by Mander *et al*. (1988), was used to consider concrete confinement. Based on modeling the response of structural walls, Waugh and Sritharan (2010), shear walls were modeled using fiber-based beam-column elements and displacement-based beam-column elements. The ratio of the mass of concrete storeys to the mass of steel storeys in this study is approximately 1.5.

5. Damping ratio and period

The damping ratios are considered as 5% and 2% for concrete and steel structures, respectively. The equivalent damping ratio of the mixed structure was calculated based on the study of Papageorgiou and Gantes (2010). The modal mass and the ratio of the upper structure period to the lower structure period were calculated in order to obtain the damping ratio of the mixed structure and estimate the equivalent damping ratio.

The fundamental periods of 5, 9 and 15 storey structures are compared in Fig. 5. As expected, the fundamental periods increase when the number of storeys increases. In all studied hybrid

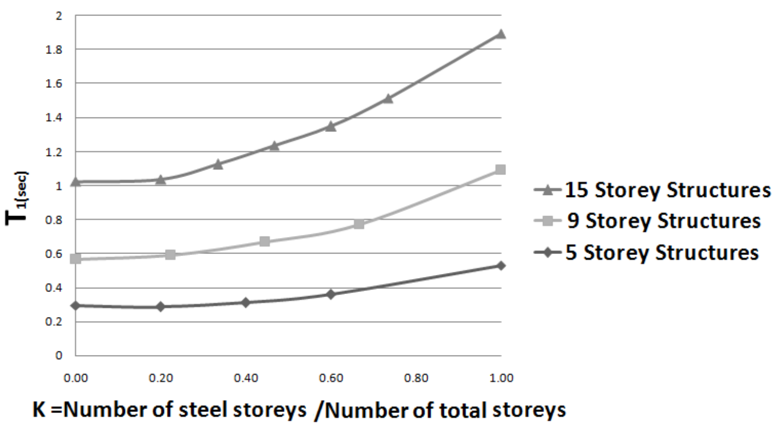


Fig. 5 Comparing the fundamental periods of structures

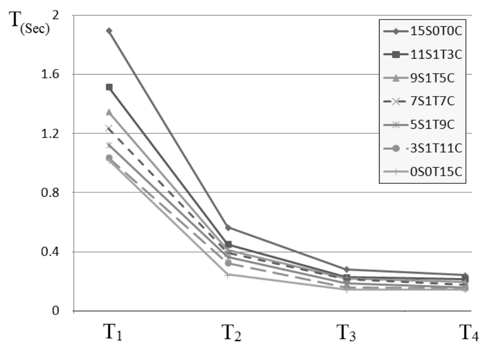


Fig. 6 The periods of 4 first modes for different 15 storey structures

structures, only the transition storey was considered. According to this figure, the fundamental periods of a structure increases with increasing the height of structure as well as the number of steel storeys. The difference between the period of first modes of concrete and absolute steel structures increases with increasing the number of storeys. This period difference is 0.3, 0.55 and 0.9 sec. for 5-, 9- and 15- storey concrete and totally steel buildings, respectively. The periods of mixed structures are between those of totally concrete and totally steel structures.

The changes in the periods corresponding to the 4 first modes are depicted in Fig. 6. Based on this figure, the periods of structures become closer to each other at the higher modes. Moreover, complete steel structures have higher periods compared to others.

6. Detecting the response modification factors through incremental dynamic analysis

6.1 IDA analysis

IDA analysis and its use in obtaining response modification factor are discussed in this section. This is a relatively new technique in which several earthquake records are chosen. Each record is incrementally applied to the structure. At the end, the curves of DM - IM are plotted for each

Table 3 The ground motion records used in IDA

Record number	Record name	Station	Soil type	Date	PGA (g)
1	Chi-Chi, Taiwan	CHY080	II	09/20/1999	0.902
2	Coyote Lake	Gilroy Array 3	II	08/06/1979	0.434
3	Kobe	KJMA	II	01/16/1995	0.821
4	Landers	Coolwater	II	06/28/1992	0.417
5	Loma Prieta	Corralitos	II	10/18/1989	0.644
6	Morgan Hill	Anderson Dam	II	04/24/1984	0.423
7	N. Palm Springs	N. Palm Springs	II	07/08/1986	0.694
8	Northridge	Santa Monica	II	01/17/1994	0.883
9	Bam	Bam	II	26/12/2003	0.767
10	Tabas	9101 Tabas	II	09/16/1978	0.917
11	Cape Mendocino	Rio Dell Overpass FF	II	04/25/1992	0.547
12	kocaeli	Sakarya	II	08/17/1999	0.226
13	Parkfield	Temblor	II	06/28/1966	0.283
14	Victoria, Mexico	Cerropieto	II	06/09/1980	0.377
15	San Fernando	Lakehughes	II	02/09/1971	0.258

scaled records (Vamvatsikos and Cornell 2002). The records of fifteen well-known earthquakes from around the world were used for IDA including two large earthquakes of Iran, Bam and Tabas, and tabulated in Table 3.

These records are registered on soil type II based on part 6 of Iranian National Building Code (2006) and site category B of USGS classification according to their shear wave velocities.

IDA curves are plotted for 11S1T3C structure as an example and presented in Fig. 7.

The necessary steps for calculating the response modification factor are as follows:

(1) Selecting IM => the spectral acceleration of the first-mode period;

(2) Selecting DM => maximum inter-storey drift ratio in all storeys during the earthquake;

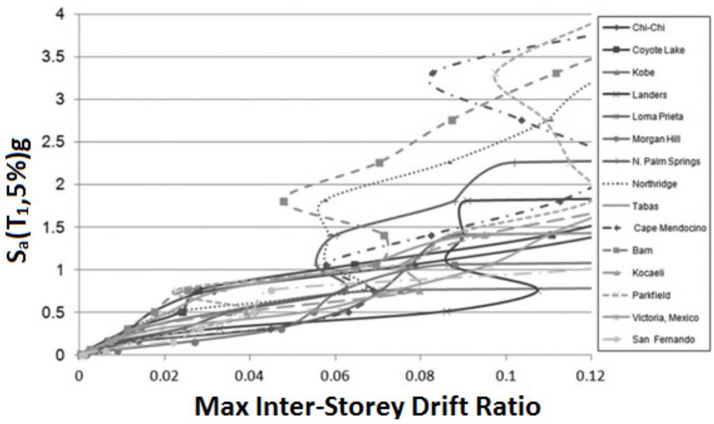


Fig. 7 IDA curves of 11S1T3C structure

(3) Selecting the earthquake records => 15 records, well-known in the world, recorded on the soil type 2;
(4) Selecting a criterion arriving DM at which, the structure is destroyed

$$T < 0.7s \quad => \quad \frac{\Delta}{h} \leq 0.025 \tag{6}$$

$$T \geq 0.7s \quad => \quad \frac{\Delta}{h} \leq 0.02 \tag{7}$$

Where T is the period, Δ is the relative displacement of storeys and h is the storey height.
(5) Selecting the earthquake scaling type to be applied to the structure => hunt and fill algorithm;
(6) Conducting IDA of hunt step: progressive increase of earthquake and finding the approximate earthquake intensity which will take DM to the criterion of step 4;
(7) Conducting IDA of fill step: finding the exact intensity of the considered earthquake => shear base at this earthquake level: $V_{b(Dyn,y)}$;
(8) Converting the model into elastic model and conducting the analysis in the seismic intensity of the 7th step => calculating the base shear at this earthquake level: $V_{b(Dyn,e)}$;
(9) Conducting pushover analysis => obtaining the shear base corresponding to the first damage: $V_{b(St,s)}$;
(10) Calculating the seismic parameters by using the results of the steps 7, 8 and 9.

6.2 Overstrength factor (R_s)

This method was presented by Mwafy and Elnashai (2002) and is used for calculating base shear through IDA. Overstrength factor is the ratio of the final base shear to the base shear corresponding to the first yielding. Based on the references; (Masumi *et al*. 2004, Asgarian and Shokrgozar 2009), Eq. (2) is modified as follows

$$R_s = V_{b(Dyn,y)} / V_{b(St,s)} \tag{8}$$

Where, R_s is overstrength factor, $V_{b(Dyn,y)}$ is dynamic base shear and $V_{b(St,s)}$ is static base shear corresponding to the first yielding in the structure. IDA was carried out using the mentioned records and damping ratios. Using Hunt and Fill tracing algorithm for IDA, a specific intensity measure at which the structure meets the target failure criteria is achieved. The base shear of the structure in the mentioned seismic intensity level is considered as $V_{b(Dyn,y)}$ (the idealized yield strength). $V_{b(Dyn,y)}$ was calculated by incremental dynamic analysis (IDA) of structures using fifteen earthquake records. The base shear, which corresponds to the first significant yield strength, $V_{b(St,s)}$, was achieved by pushover analysis because the point of the first yielding cannot be distinguished easily during IDA analysis.

The lateral forces were increased gradually in pushover analysis to give $V_{b(St,s)}$ parameter.

It means that the linear ultimate strength of the structure was assumed to be the same in nonlinear static and nonlinear dynamic analysis, (Mwafy and Elnashai 2002, Masumi *et al*. 2004, Fanaie and Ezzatshoar 2014, Fanaie and Afsar 2014).

Table 4 Overstrength, ductility and response modification factors for 11S1T3C structure

Record	S_a (T_1 , %5) g	Max drift	V_s (kgf)	V_y (kgf)	V_e (kgf)	R_s	R_μ	Y	R	R_ω
Bam	0.64	0.019	348535.3	442313.4	808374.6	1.269	1.828	1.44	2.319	3.340
Chi-Chi	0.55	0.019	348535.3	437197.2	550193.2	1.254	1.258	1.44	1.579	2.273
Coyote Lake	0.44	0.020	348535.3	485858.7	791685.0	1.394	1.629	1.44	2.271	3.271
Kobe	0.43	0.018	348535.3	432437.4	782079.5	1.241	1.809	1.44	2.244	3.231
Landers	0.25	0.019	348535.3	379775.8	526863.7	1.090	1.387	1.44	1.512	2.177
Loma Prieta	0.19	0.020	348535.3	439852.4	617031.4	1.262	1.403	1.44	1.770	2.549
Morgan Hill	0.13	0.021	348535.3	501836.0	712607.8	1.440	1.420	1.44	2.045	2.944
N. Palm Springs	0.27	0.019	348535.3	597973.1	767710.6	1.716	1.284	1.44	2.203	3.172
Northridge	0.45	0.020	348535.3	468407.2	769406.6	1.344	1.643	1.44	2.208	3.179
Tabas	0.51	0.021	348535.3	522122.5	943749.9	1.498	1.808	1.44	2.708	3.899
Cape Mendocino	0.19	0.021	348535.3	466823.7	591176.3	1.339	1.266	1.44	1.696	2.442
Kocaeli	0.39	0.019	348535.3	510146.9	733673.1	1.464	1.438	1.44	2.105	3.031
Parkfield	0.23	0.021	348535.3	582738.7	955576.5	1.672	1.640	1.44	2.742	3.948
Victoria, Mexico	0.31	0.020	348535.3	516509.1	610025.6	1.482	1.181	1.44	1.750	2.520
San Fernando	0.15	0.021	348535.3	717631.0	820639.8	2.059	1.144	1.44	2.355	3.391
Average		0.020	348535.3	500108.2	732052.9	1.435	1.476	1.44	2.100	3.025

6.3 Ductility reduction factor (R_μ)

The intensity measure which will damage the structure up to certain failure limit state was obtained by IDA using the scaled earthquake records. Linear dynamic analysis was then carried out under the same intensity measure of earthquake record to calculate the base shear corresponding to elastic behavior, $V_{b(Dyn,e)}$ (Mwafy and Elnashai 2002). The elastic materials were used for all elements in the linear analysis of the structure. Geometric imperfections were not considered in the steel elements; however, linear coordinate was applied for all elements. Finally, the ductility reduction factor was calculated using Eq. (1). The value of allowable stress factor is determined on the basis of design attitude which is about 1.4-1.7. This coefficient was taken as 1.44 in this study based on the recommendations of UBC-97.

Using Eqs. (1) to (5), overstrength, ductility and response modification factors were calculated for all modeled structures in both allowable stress design and ultimate state design methods. These factors, related to 11S1T3C structure, are given in Table 4, as an example.

7. Results

7.1 Push over analysis

Nonlinear static analysis was conducted and pushover curves were plotted using the result obtained by OpenSees software. The values of static base shear equivalent to the first significant yield strength, $V_{b(St,s)}$, in the structure were derived from Figs. 8-10. They are summarized in Table 5 for the structures with different storeys. According to Figs. 8-10, by increasing the number of steel storeys in the mixed structures, their stiffness and lateral load-carrying capacity decrease.

According to the pushover curves of 5-storey structures, the more the structure approaches a complete steel structure, the more the ultimate deformation and the less the maximum (ultimate) load of the structure. Generally, by increasing the number of steel storeys in the mixed structures, their stiffness, first significant yield strength (V_s) and idealized yield strength (V_y) decrease.

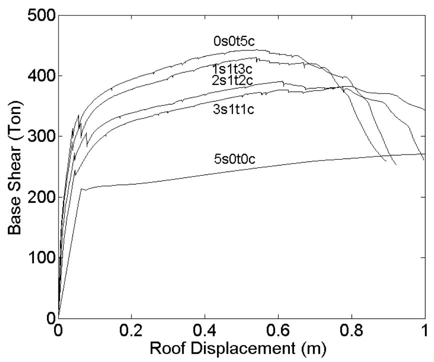


Fig. 8 Pushover analysis curves of 5 storey structuresd

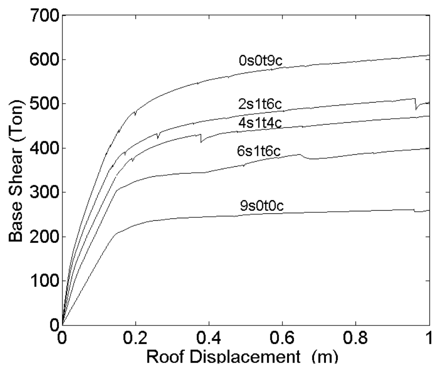


Fig. 9 Pushover analysis curves of 9 storey structures

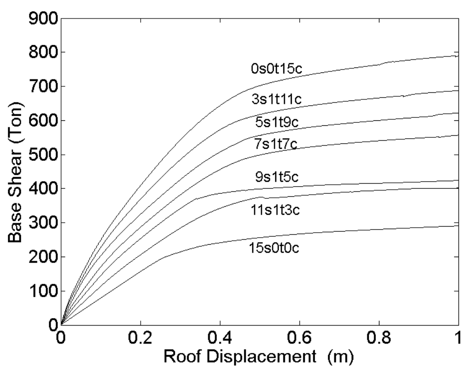


Fig. 10 Pushover analysis curves of 15 storey structures

7.2 Response modification factor

The average values of overstrength, ductility and response modification factors of 5, 9 and 15 storey structures are presented in Table 5. The structures were modeled with the proposed seismic response modification factors in order to verify the results. IDA was then conducted on the re-modeled structures. The procedure for obtaining R factor values was repeated. The results were found to be similar to the previous ones and are tabulated in Table 5.

Based on Table 5, ductility factor value is lower in all mixed structures compared to concrete or steel ones with the same heights. However, only the values of overstrength factor are lower in the 9- and 15- storey mixed structures in comparison to those of steel and concrete ones with the same heights. This fact causes the response modification factor of 5-storey mixed structure not to decrease dramatically. However, this factor significantly decreases in the 9- and 15- storey mixed structures. It is noteworthy that there is something common in the designing of steel, concrete and 5- storey mixed structures which is the use of equivalent static method according to the codes; while other mixed structures were designed through spectral dynamic analysis.

The response modification factors, corresponding to 5, 9 and 15 storey structures are depicted in Figs. 11-13, respectively, regarding allowable stress design method. In these figures, the response modification factor is presented on the vertical axis and the ratio of the number of steel storeys to the total number of storeys (*K*) on the horizontal axis. By increasing the height of structures, the value of response modification factor decreases. According to these charts, response modification factors of complete steel or concrete structures are higher than those of mixed

Table 5 Response modification factors of structures and the values of response modification factor obtained from the first and second analyses

Name	DM (Max drift)	V_s (kgf)	V_y (kgf)	V_e (kgf)	R_s	R_μ	Y	R	R_ω	R_ω factor of second analysis
5S0T0C	0.025	1965663	285413	1154104	1.45	4.04	1.44	5.86	8.45	8.52
3S1T1C	0.025	242586	386371	1202191	1.59	3.16	1.44	4.95	7.13	7.25
2S1T2C	0.025	268832	438745	1283168	1.64	2.96	1.44	4.78	6.89	7.02
1S1T3C	0.025	288677	471029	1412788	1.63	3.02	1.44	4.89	7.05	7.22
0S0T5C	0.025	315802	495830	1730168	1.57	3.49	1.44	5.48	7.89	7.95
9S0T0C	0.02	197479	268875	755482	1.36	2.81	1.44	3.82	5.5	5.58
6S1T2C	0.02	284905	407792	640992	1.43	1.56	1.44	2.25	3.24	3.31
4S1T4C	0.025	382306	472701	845529	1.24	1.78	1.44	2.2	3.18	3.26
2S1T6C	0.025	399699	570786	1162277	1.43	2.05	1.44	2.91	4.19	4.29
0S0T9C	0.025	480065	771950	1640223	1.6	2.12	1.44	3.42	4.92	4.85
15S0T0C	0.02	230771	347933	714242	1.5	2.03	1.44	3.09	4.45	4.41
11S1T3C	0.02	348535	500108	732052	1.53	1.48	1.44	2.1	3.02	3.11
9S1T5C	0.02	346522	614048	955202	1.77	1.54	1.44	2.76	3.97	3.85
7S1T7C	0.02	470560	576460	913390	1.22	1.58	1.44	1.94	2.79	2.91
5S1T9C	0.02	530071	659660	991039	1.24	1.52	1.44	1.87	2.69	2.82
3S1T11C	0.02	571905	694447	1079644	1.21	1.57	1.44	1.89	2.72	2.95
0S0T15C	0.02	658899	979133	1743720	1.49	1.83	1.44	2.65	3.81	3.78

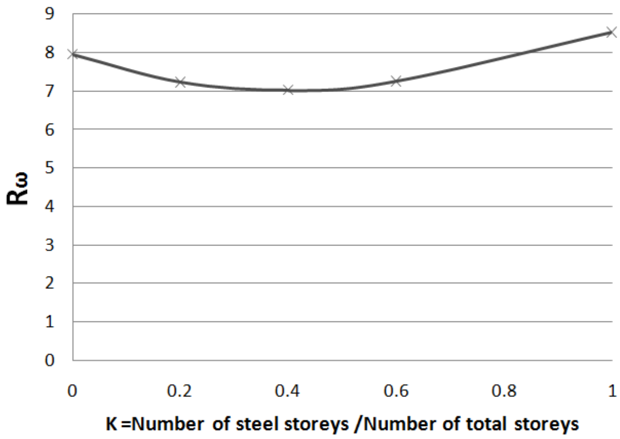


Fig. 11 Response modification factors for 5 storey structures

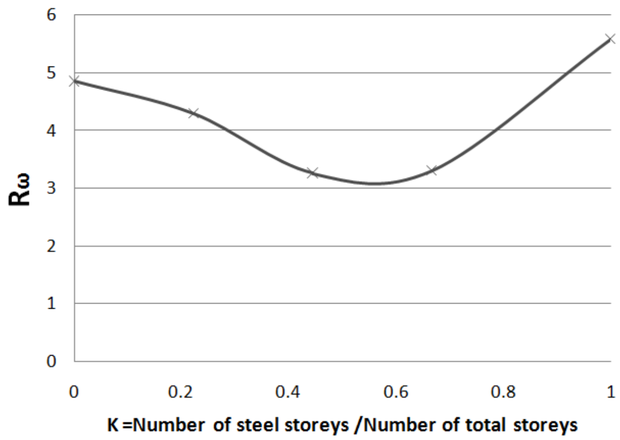


Fig. 12 Response modification factors for 9 storey structures

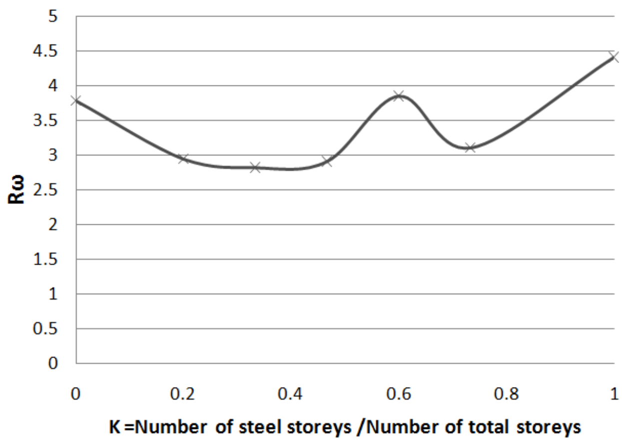


Fig. 13 Response modification factors for 15 storey structures

structures. This fact could be due to the irregularity of lateral loading system and the kind of material used at different heights. According to Figs. 9-11, in the 5-storey buildings, the highest difference of response modification factor values between mixed and totally steel structures is 1.5, and those of mixed and concrete structures is 1. The ratio of this reduction to the response modification factor of the concrete structure is 0.125. Slight differences are seen between the response modification factor values of 5-storey mixed structures. In the 9-storey structures, the highest difference of response modification factor values between mixed and steel structures is 2.5, and those of mixed and totally concrete structures is 2. The ratio of this reduction to the response modification factor of concrete structure is 0.4. However, the response modification factors of 9-storey structures are different from each other, unlike 5-storey buildings. In general, it can be said that a dramatic reduction occurred in K = 0.4. In the 15-storey buildings, the highest difference of response modification factor values between mixed and totally steel and concrete structures are 1.75 and 1 respectively. The ratio of this reduction to the response modification factor of concrete structure is 0.25. The highest response modification factor reduction was in the 9- storey buildings. This dramatic reduction is also seen in the response modification factor of 9-storey mixed structures with the period lower than 0.7 sec. It means that the changing inter-storey drift ratio from 0.025 to 0.02 in the 0.7 sec period has no significant effect in the mentioned reduction.

As all mixed structures have only one transition storey, the response modification factor can be considered as a function of the variables of the number of steel storeys (N_s) and the number of concrete storeys plus one (N_c); one is the number of transition storeys.

Multiple linear regressions were conducted on the obtained results in this research and SPSS software in order to assess the relation between seismic parameters of the structures with steel and concrete storeys. In consequence, the models were obtained in which the independent variables are the numbers of steel and concrete storeys with a transition storey and the dependent ones are response modification factor, overstrength factor and the first mode period of the structures. The relations obtained from SPSS software were converted through mathematical calculations to the ones in which K is the ratio of the number of steel storeys to the total number of storeys and N is the total number of storeys. The obtained relations are expressed as follows

(a) Response modification factor

- Allowable Stress Design (ASD) method

$$R_{\omega}(N,K) = (0.06K - 0.408)N + 8.729, R = 0.849 \tag{9}$$

- Limit State Design (LSD) method

$$R_{\omega}(N,K) = (0.042K - 0.283)N + 6.062, R = 0.849 \tag{10}$$

(b) Ductility Reduction Factor

$$R\mu(N,K) = (0.027K - 0.169)N + 3.877, R = 0.846 \tag{11}$$

(c) Overstrength factor

There is no correlation between overstrength factor and number of storeys. This factor is about 1.5 (in the range of 1.2-1.8)

(d) The first period of structures

$$T_1(N,K) = (0.058K + 0.067)N - 0.108, R = 0.99 \tag{12}$$

Where, K is the ratio of the number of steel storeys to the total number of storeys. N is the total number of storeys and R is the coefficient of multiple correlation. R is a measure of the strength of the association between the independent variables and the one dependent variable. The coefficient of multiple correlation has values between zero and one; a higher value indicates a better predictability of the dependent variable from the independent variables, with a value of one indicating that the predictions are exactly correct and a value of zero indicating that no linear combination of the independent variables is a better predictor than the fixed mean of the dependent variable. No other values of R have precise definitions. The below values can be considered as the simplistic expression of this factor:

R = 0.9, strong association; R = 0.5, moderate association; R = 0.25, weak association.

8. Conclusions

Over 4600 nonlinear analyses were conducted in this research using earthquake records. Consequently, response modification factor, ductility factor and overstrength factor were calculated for the structures. For this purpose, 17 structures of 5, 9 and 15 storeys with different number of concrete and steel storeys were subjected to 15 well-known earthquake records in order to conduct IDA and nonlinear static analyses. Considering the selected models and the records registered on the soil with moderate shear velocities of 375-750 m/sec, the obtained results are valid for structures of up to 15 storeys in the regions of high seismicity and the mentioned type of soil. According to the results obtained in this research:

- The values determined for response modification factors of mixed structures are lower than those of complete steel or concrete structures of the same heights.
- The ratio of maximum response modification factor reduction of mixed structures to the response modification factor of concrete structures of the same heights are about 12.5%, 40% and 20% in the 5-, 9- and 15- storey buildings, respectively.
- The response modification factor is lower in the mixed structures compared to steel or concrete structures of the same heights; this is more obvious in the 9- storey structures in comparison to those of 5- and 15- storey buildings. Therefore, it suggests that the construction of mixed structures of the mentioned height would be very risky. It is suggested that mixed structures should not be used in buildings with the aforementioned storeys and most particularly, where the ratio of the number of steel storeys to the total number of storeys is over 0.25.
- The formulas are proposed for the mentioned factors based on the results obtained in this research and presented as follows:

(a) Response modification factor

\- Allowable Stress Design (ASD) method:

$$R_\omega(N,K) = (0.06K - 0.408)N + 8.729, R = 0.849$$

- Limit State Design (LSD) method:

$$R_{\omega}(N,K)=(0.042K-0.283)N+6.062, R=0.849$$

(b) Ductility Reduction Factor

$$R_{\mu}(N,K)=(0.027K-0.169)N+3.877, R=0.846$$

(c) Overstrength factor
Actually there is no correlation between overstrength factor and number of storeys. This factor is about 1.5 (in the range of 1.2-1.8)
(d) The first period of structures

$$T_1(N,K)=(0.058K+0.067)N-0.108, R=0.99$$

Where, K is the ratio of the number of steel storeys to the total number of storeys. N is the total number of storeys;

- By increasing the number of steel storeys in mixed structures, their periods and ultimate deformation are increased while their stiffness, first significant yield strength (V_s) and idealized yield strength (V_y) decrease. The difference between the first mode period of concrete structures and that of complete steel ones increases with increasing the number of storeys. This difference is about 0.3 sec. in the 5- storey, 0.55 sec. in the 9- storey and 0.9sec.in the 15- storey buildings. The period of mixed structures is between these values. The periods of all co-heights structures come closer to each other in the upper modes.

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