Structural Engineering and Mechanics, Vol. 28, No. 5 (2008) 571-585
DOI: http://dx.doi.org/10.12989/sem.2008.28.5.571

Earthquake behavior of stiffened RC frame structures with/without subsoil

Y. I. Özdemir† and Y. Ayvaz‡

Department of Civil Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

(Received June 7, 2005, Accepted January 23, 2008)

Abstract. The purpose of this study is to investigate the linear earthquake behavior of the frame structures including subsoil with different stiffening members and to compare the results of each frame considered. These comparisons are made separately for displacement, bending moments and axial forces for frames with different storey and bay numbers for the time history and the modal analyses. The results of both methods are also compared. The results of the frames with subsoil are also compared with the results of the frames without subsoil. It is concluded that all stiffening members considered in this study decrease the lateral displacement of the frame and the bending moment of the columns and increase the axial force in the columns and that configuration of the bracing members come out to be an important parameter in braced frames since the frames with the same type of bracing give different results depending on configuration. It is also concluded that, in general, the absolute maximum displacements of the frames modeled with subsoil are larger than those of the frames modeled without subsoil.

Keywords: earthquake behavior; frame structure; moment-resisting frames; braced frames; frames with shear walls; stiffening members; comparative study.

1. Introduction

Earthquakes occurred in the past that caused the deaths of a lot of people made human being design the structures resistant to earthquakes. The idea of earthquake resistant structure is almost as old as the structural history. Human being concentrates more on the earthquake resistant structural design after each earthquake. The principles of the design of earthquake resistant structures all over the world are almost the same depending on the intensity of the earthquake.

As well known that in the earthquake resistant structural design, selection of the type of the structural form is very important, and the following factors should be considered in this selection: (a) light building, (b) simplicity, symmetry and regularity, (c) uniformity and continuity, (d) length and shape in plan, (e) shape in elevation, (f) balanced stiffness and strength, (g) failure modes, (h) well separated or well integrated non-structural components, (i) foundation conditions (Dowrick 1987, Ayvaz and Aydemir 2000, Özdemir and Ayvaz 2002). There are many references on one or more of these factors in the technical literatures (Newmark and Rosenblueth 1971, Rosenblueth 1980, Ambrose and Vergun 1985, Dowrick 1987, Ersoy and Çıtıpıtıoğlu 1988, Pubal 1988, Celep and Kumbasar 1993, Ayvaz and Aydemir 2000, Özdemir and Ayvaz 2002).

† C. Eng., E-mail: yaprakozdemir@hotmail.com
‡ Professor, Corresponding author, E-mail: ayvaz@ktu.edu.tr

Human being uses different systems for earthquake resistant structure depending on the developments. In early times, it was thought that the structures can be affected less from the ground motions by keeping the rigidity of the first floor small ('soft first storey'). By this way, it is tried to keep structure away from the ground motion with shorter period. In order to have this situation, in addition to the ideal plastic hinge at the ends of the columns, large sway at the top of the structure should occur. Since it is very difficult to have these two conditions, the structures with small first floor rigidity are not appropriate one to be resistant against earthquakes (Celep and Kumbasar 1993, Ayvaz and Aydemir 2000, Özdemir and Ayvaz 2002, Reitherman 2005).

One of the systems used for earthquake resistant structure is the base isolations (Dowrick 1987, Jangid 1996). Even tough these systems depend on the principle of the soft first storey, it is known that they have been effectively used in a number of structures all over the world (Fan and Ahmadi 1990). Since application of the base isolation systems is difficult and needs qualified workers, many researchers have chosen the way in which the rigidity of the structure is increased to decrease the displacement due to earthquakes. For this, the main structural forms suitable for earthquake resistance are: a) Moment-resisting frames, b) Shear walls, c) tube structures, d) braced frames and e) hybrid structural systems (Newmark and Rosenblueth 1971, Rosenblueth 1980, Ambrose and Vergun 1985, Dowrick 1987). Each form has its advantages and disadvantages (Ayvaz and Aydemir 2000, Özdemir and Ayvaz 2002, Saatcioglu and Humar 2003, Jayachandran 2004, Reitherman 2005).

Moment-resisting frames used widely all over the world tend to sway excessively under lateral loads, such as earthquake loads, but avoiding brittle shear failure modes is their important advantage. Shear walls are also used in many structures. The great advantage of these walls is to limit the inter-storey deflection since they are generally very rigid, but they exhibit brittle shear failure modes as seen in several earthquakes (Dowrick 1987). Also, they do not provide overall safety of structure in an earthquake because they rigidify partly the structure. Tube structures are the combination of shear walls or columns placed closely and connected to each other by strong beams (Ersoy and Çıtıpıtıoğlu 1988, Jayachandran 2004). These types of structures may be considered between moment-resisting frames and shear walls. Braced frames are constructed by using bracing members (Dowrick 1987). These members can be external and/or internal. Externally bracing is constituted by the use of struts, guys, buttresses, etc. and internally bracing can be made by one or more diagonal members within the structure. Being to simpler to design, cheaper to construct, and more resistant to large lateral displacements and brittle connection fractures than traditional moment-resisting frame construction, braced frames, however, considerable damage has been noted in concentric braced frames following several recent earthquakes, including the 1985 Mexico (Osteraas and Krawinkler 1989), 1989 Loma Prieta (Kim and Goel 1992), 1994 Northridge (Tremblay *et al.* 1995, Krawinkler *et al.* 1996), and 1995 Hyogo-ken Nanbu (AIJ 1995) earthquakes. Hybrid structural systems are the combination of two or more of above systems.

It should be noted that the last four structural forms are generally more rigid than the moment-resisting frames, have less reliable ductility, but it is understandable that the degree of ductility needed decreases with increasing rigidity (Kalyanaraman *et al.* 1998). These frames are more inclined to undesirable buckling modes, and if the diagonal members are very slender and hence capably of tensile resistance only, the seismic resistance of the structure is not as good as when they are capably of tensile and compression resistances. There are many references in the technical literature about buckling of columns in braced frames, such as Goncalves (1991).

Jayachandran (2004) described several structural systems and presented approximate methods of analysis for several of them. Gordon (2005) analyzed and designed two prototype of the full height truss frame. Choi *et al.* (1992) proposed a simplified approach, termed as "correction factor method" for the problem of the effect of the sequential application of dead load in the analyses of multi-storey frames. Choi and Kim (1985) studied multi-storey frames subjected to sequential gravity loads. Taskin and Hasgür (2006) studied the non-linear analysis of RC 3D shear wall-frame structure by a coded computer program based on Monte Carlo simulation technique.

There are many types of bracing and some problems in planning of them. The types of bracing commonly used are X-bracing, K-bracing, diagonal bracing, diagonal-yielding bracing and knee bracing (Ayvaz *et al.* 1997, Ayvaz and Aydemir 2000, Özdemir and Ayvaz 2002, Saatcioglu and Humar 2003, Reitherman 2005, Çavdar 2005, Öztürk 2005). Each one has its advantages and disadvantages when they are compared to each other (Ambrose and Vergun 1985, Dowrick 1987). According to the capacity design procedure, braces are chosen as the primary seismic resisting elements, which produce the over strength axial tension and compression actions (Remennikov and Walpole 1998).

In this study, among all five structural forms shortly explained above, in addition to moment-resisting frame, linear analysis of reinforced concrete frames stiffened with X-bracing, two different configurations of diagonal bracing and shear walls are analyzed when they are subjected to earthquakes since engineers designing application projects generally use the linear analysis in their designs. The purpose of this study is to investigate the effects of different stiffening members on the linear earthquake behavior of frame structures with/without subsoil and to compare the results of each frame considered. These comparisons are made separately for displacements, bending moments and axial forces for frames with different storey and bay numbers for the time history (THA) and modal (MA) analyses. The results of both methods are also compared. The frame structures considered are 10, 7, and 5 storeys with the combination of 4, and 3 bays. It is assumed that the diagonal members are capably of tensile and compression resistances. As earthquake loading, the spectrum velocities of East-West component of the March 13, 1992 Erzincan Earthquake (Ayvaz *et al.* 1997) is used in order to see the behavior of the stiffened RC structures subjected to this earthquake since this earthquake has the largest peak acceleration value recorded in recent years in the Eastern Turkey, and it is given in Fig. 1.

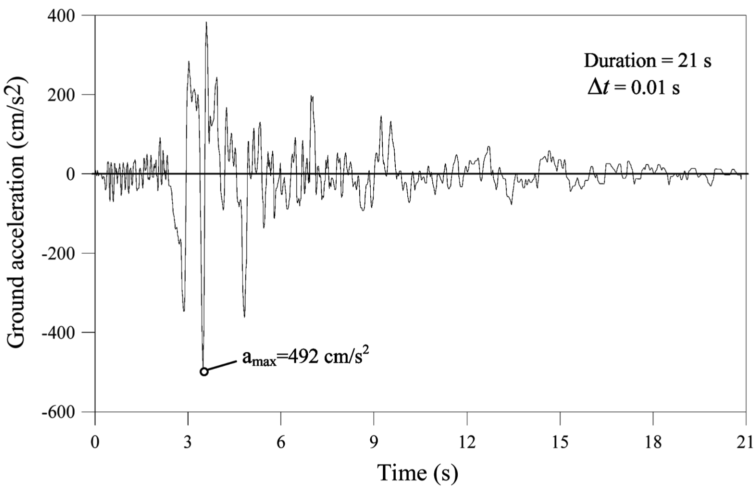
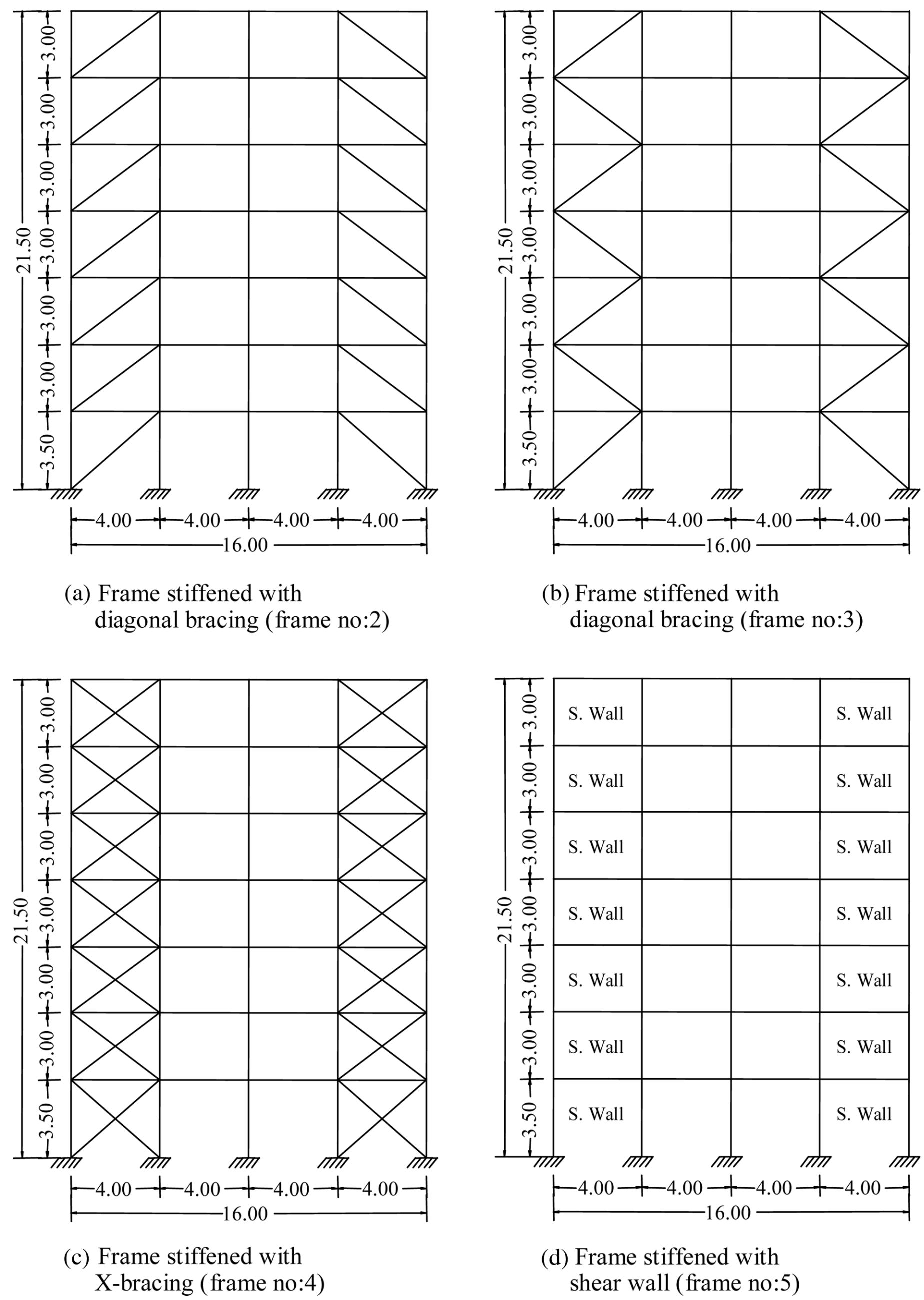


Fig. 1 East-West component of the March 13, 1992 Erzincan earthquake in Turkey

2. Numerical examples

2.1 Data

In addition to the moment-resisting frame (frame no: 1), frame structures and their stiffening



(a) Frame stiffened with diagonal bracing (frame no:2)

(b) Frame stiffened with diagonal bracing (frame no:3)

(c) Frame stiffened with X-bracing (frame no:4)

(d) Frame stiffened with shear wall (frame no:5)

Fig. 2 The sample frames used in this study member types used in this study are given in Fig. 2 for the frames with 7 storeys and four bays. As seen from this figure, one of these frames is the frame with diagonal bracing (Fig. 2(a)), another one is the frame with different configuration of the diagonal bracing (Fig. 2(b)), other one is the frame with X-bracing (Fig. 2(c)) and the last one is the frame with shear walls (Fig. 2(d)). The frames with 10 and 5 storeys with the combinations of 4 and 3 bays are not given because the same stiffening members are used in these frames. As seen from Fig. 2, the height of the first storey is taken to be 3.5 m and these of the others are taken as 3.0 m. The span lengths of all bays are taken to be 4.0 m. The cross-section dimensions of the columns, beams and bracing members in all frames are taken to be 400 mm×900 mm, 250 mm×500 mm, 300 mm×300 mm, respectively, and kept constant at all storeys. The thickness of the shear wall in frame no: 5 is taken to be 200 mm.

Material properties used are as follows: Modulus of elasticity (E) = 2.7×10^7 kN/m^2, Poisson's ratio = 0.2, and unit weight of reinforced concrete = 25 kN/m^3 as suggested in TS500 (2000). For the masses of the columns, beams, and stiffening members, different values are used depending on the cross-section dimensions and the loads on them. In calculation of the masses of the beams, a slab with 4 m span and 0.12 m thickness is also considered at each side of the each beam. In the analysis, the first five modes of the frames are considered. A constant damping ratio of 2% is used for all modes considered to be conservative in the results.

For the sake of accuracy in the results, rather than starting with a set of finite element mesh size and time increment, the mesh size and time increment to produce the desired accuracy are determined. This analysis is done separately for the mesh size and time increment. To find out the required mesh size, the time increment is fixed, and convergence of the absolute maximum displacement is checked for different mesh sizes. To find out the required time increment, the mesh size is fixed, and convergence of the absolute maximum displacement is checked for different time increments. In conclusion, the results have an acceptable error when using 0.01 s. time increment if each column, beam, and diagonal are considered to be one element except that another node is considered at the intersection of X-bracing (see Fig. 2(c)).

The same frames are also studied by modeling with subsoil. In the modeling of the frames including subsoil, the depth of the subsoil is taken to be a half height of the frame and the width of the subsoil is taken to be the sum of the width of the frame and twice the height of the frame. It is assumed that the behavior of the subsoil is also linear. Material properties used for subsoil are as follows: Modulus of elasticity (E) = 1.9×10^4 kN/m^2, Poisson's ratio = 0.3, and unit weight of the subsoil = 19 kN/m^3. In modeling of the subsoil, 4-noded quadrilateral elements are used. The dimensions of the elements used in the subsoil mesh are not the same. They are changed by depending on the closeness to the frame. The dimensions of the finite elements which are closer to the frame are smaller than the others which are away from the frame.

2.2 Results

In this study, the absolute maximum displacements, bending moments, and axial forces of all frames are given since maximum values of these quantities are the most important ones for design. The absolute maximum displacement, bending moment, and axial force values of all frames considered in this study are given in Table 1, and Table 2. These quantities are also presented in graphical forms, to understand better the effects of the stiffening members, storey number, bay number and subsoil on the absolute maximum responses such as displacement, bending moment and axial force.

Depending on these parameters mentioned above, the absolute maximum displacements are given

Table 1 The absolute maximum displacement, bending moment, and axial forces of all frames modeled without subsoil

Storey number	Bay number	Frame number	Absolute maximum displacement (m)		Absolute maximum bending moment (kNm)		Absolute maximum axial force (kN)	
			MA	THA	MA	THA	MA	THA
10	4	1	0.4890	0.2657	5293	3061	6795	3688
10	4	2	0.2604	0.2533	2392	2451	15300	14590
10	4	3	0.2502	0.2499	2564	2609	13930	13840
10	4	4	0.2136	0.2177	1682	1692	15490	15720
10	4	5	0.1377	0.1306	608	606	10360	10060
7	4	1	0.2323	0.2233	3762	3625	3387	3267
7	4	2	0.0365	0.0484	622	865	2947	3907
7	4	3	0.0400	0.0528	744	1086	2960	3899
7	4	4	0.0401	0.0425	556	589	4449	4703
7	4	5	0.0614	0.0636	533	565	7897	8256
5	4	1	0.1067	0.1072	2531	2585	1613	1625
5	4	2	0.0407	0.0431	1180	1308	4669	4992
5	4	3	0.0529	0.0547	1652	1753	5317	5517
5	4	4	0.0167	0.0198	421	532	2644	3163
5	4	5	0.0151	0.0171	251	306	3158	3672
10	3	1	0.4949	0.2680	5127	2924	6880	3725
10	3	2	0.1857	0.1834	1654	1830	11160	11140
10	3	3	0.2037	0.2069	2017	2122	11650	11830
10	3	4	0.1525	0.1418	1064	921	11270	10390
10	3	5	0.0978	0.1042	428	466	7461	8020
7	3	1	0.2333	0.2237	3654	3537	3409	3278
7	3	2	0.0400	0.0415	682	751	3279	3399
7	3	3	0.0373	0.0417	690	774	2812	3138
7	3	4	0.0571	0.0568	786	781	6446	6457
7	3	5	0.0535	0.0561	464	487	6957	7293
5	3	1	0.1059	0.1068	2443	2492	1605	1624
5	3	2	0.0195	0.0224	579	717	2191	2551
5	3	3	0.0293	0.0326	918	1073	2866	3202
5	3	4	0.0203	0.0240	518	601	3269	3862
5	3	5	0.0066	0.0075	111	164	1406	1977

in Figs. 3, and 4, the absolute maximum bending moments are presented in Figs. 5, 6, 7, 8, and 9, and the absolute maximum axial forces are shown in Figs. 10, 11, 12, 13, and 14.

As seen from Table 1, and 2, and Figs. 3, and 4, the largest absolute maximum displacement occurs in moment-resisting frame modeled including subsoil with 10 storeys and 3 bays for MA. It is 0.5746 m. Those of the other frames are less. With respect to the absolute maximum displacement of 10 storeys-3 bays moment-resisting frame modeled including subsoil, the decreases in the absolute maximum displacements are 47% (from 0.5746 m to 0.3032 m), 48% (from 0.5746 m to 0.3014 m),

Table 2 The absolute maximum displacement, bending moment, and axial forces of all frames modeled with subsoil

Storey number	Bay number	Frame number	Absolute maximum displacement (m)		Absolute maximum bending moment (kNm)		Absolute maximum axial force (kN)	
			MA	THA	MA	THA	MA	THA
10	4	1	0.5719	0.2791	5634	3923	6730	3548
10	4	2	0.3482	0.2874	3476	2582	12308	11800
10	4	3	0.3557	0.2809	3666	2705	12197	11210
10	4	4	0.3307	0.2996	3181	2617	13050	13000
10	4	5	0.2998	0.3051	3399	3500	10418	11660
7	4	1	0.2693	0.2613	4149	4109	3511	3845
7	4	2	0.1877	0.1666	2879	2598	8012	7174
7	4	3	0.1952	0.1797	3078	2787	7978	7162
7	4	4	0.1705	0.1552	2493	2304	8714	8133
7	4	5	0.1515	0.1472	2416	2417	6892	7035
5	4	1	0.1604	0.1389	3402	3495	2120	1833
5	4	2	0.0414	0.0476	937	1077	2097	2319
5	4	3	0.0407	0.0497	948	1165	1959	2312
5	4	4	0.0431	0.0459	884	961	2771	2819
5	4	5	0.0548	0.0475	1054	924	2745	2416
10	3	1	0.5746	0.2822	5472	3774	6796	3549
10	3	2	0.2971	0.3074	2956	2948	10817	12760
10	3	3	0.2975	0.3040	3024	2905	10570	12310
10	3	4	0.3014	0.3117	2938	3008	12065	13770
10	3	5	0.3032	0.3027	3483	3647	10489	11490
7	3	1	0.2657	0.2565	4031	4049	3459	3720
7	3	2	0.1485	0.1464	2296	2279	6350	6793
7	3	3	0.1547	0.1485	2432	2375	6353	6567
7	3	4	0.1332	0.1429	1645	2143	7111	7885
7	3	5	0.1234	0.1377	1978	2360	5578	6862
5	3	1	0.1552	0.1381	3253	3451	2076	1891
5	3	2	0.0485	0.0462	1098	1030	2412	2046
5	3	3	0.0457	0.0458	1058	1051	2172	1944
5	3	4	0.0576	0.0520	1209	1056	3588	3045
5	3	5	0.0607	0.0566	1248	1116	3277	2905

and 48% (from 0.5746 m to 0.2971 m) for the frames stiffened with shear wall, X-bracing, and diagonal bracing (frame no: 2), respectively. If the comparison is made according to the storey number, for the 3 bays frames modeled including subsoil for MA, the decreases in the absolute maximum displacements from 10 storeys frame to 5 storeys frame is 73% (from 0.5746 m to 0.1552 m) for the moment-resisting frame, 81% (from 0.3014 m to 0.0576 m) for the frame stiffened with X-bracing, 80% (from 0.3032 m to 0.0607 m) for the frame stiffened with shear wall, and 85% (from 0.2975 m to 0.0457 m) for the frame stiffened with diagonal bracing (frame no: 3). As also

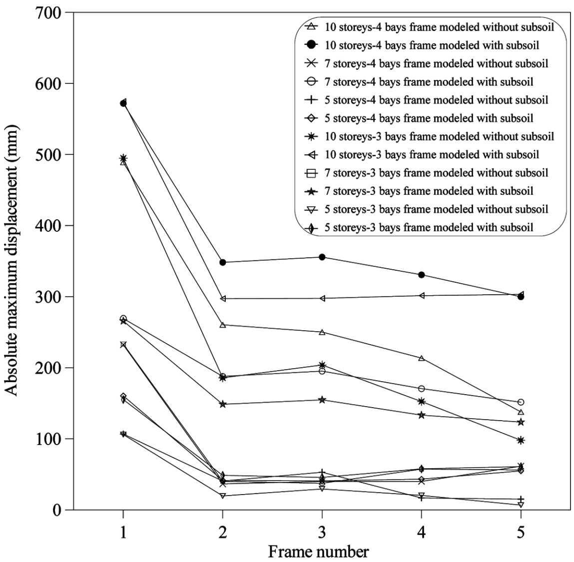


Fig. 3 Absolute maximum displacements of the frames analyzed with MA

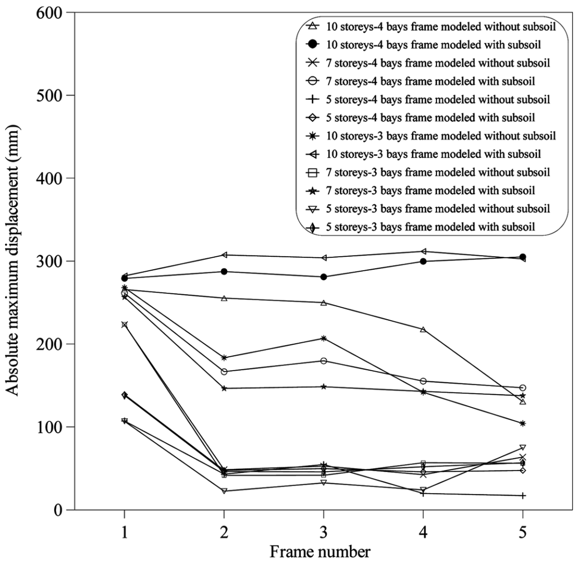


Fig. 4 Absolute maximum displacements of the frames analyzed with THA

seen from Tables 1, and 2, Figs. 3, and 4, in general, 4 bays frames have larger absolute maximum displacements than 3 bays frames and the frames modeled with subsoil have larger absolute maximum displacements than the frames modeled without subsoil. If a comparison is made according to the storey number, 10 storeys frames have larger absolute maximum displacements than 7 storeys frames, and 7 storeys frame have larger absolute maximum displacements than 5 storeys frames, except frame no: 2 and 3 with 7 and 5 storeys and 4 bays.

In general, the absolute maximum displacements of the frames stiffened with shear wall are less than those of the other frames considered. The absolute maximum displacements of the frames modeled including subsoil are larger than those of the frames modeled not including subsoil. The difference between the results of these two cases is not negligible from the design point of view. Generally MA gives a little larger absolute maximum displacement than THA.

As seen from Tables 1, and 2 and Figs. 5, and 6, the largest absolute maximum bending moments occur in the moment-resisting frame with 10 storeys and 4 bays, modeled with subsoil for MA. The absolute maximum bending moments decrease rapidly from 5634 kNm to 3181 kNm (44%) if the frames stiffened with X-bracing (frame no: 4) are used instead of moment-resisting frames. This decrease is 40% (from 5634 kNm to 3399 kNm) for the frame stiffened with shear wall (frame no: 5), 38% (from 5634 kNm to 3476 kNm) for the frame stiffened with diagonal bracing (frame no: 2), and 35% (from 5634 kNm to 3666 kNm) for the frame stiffened with diagonal bracing (frame no: 3). As also seen from Tables 1, and 2 and Figs. 5, and 6, the absolute maximum bending moments of the frames modeled with subsoil are larger than those of the frames modeled without subsoil. It can also be seen from these tables and figs. that the frames stiffened with shear walls have the minimum absolute maximum bending moment values among the frames analyzed in this study if the subsoil is not taken into consideration. If the subsoil is taken into consideration, frames no: 4 have the minimum absolute maximum bending moment.

As seen from Figs. 7, 8, and 9, the absolute maximum bending moments of 4 bays frames are larger than those of 3 bays frames. If the comparison is made according to the storey number, the

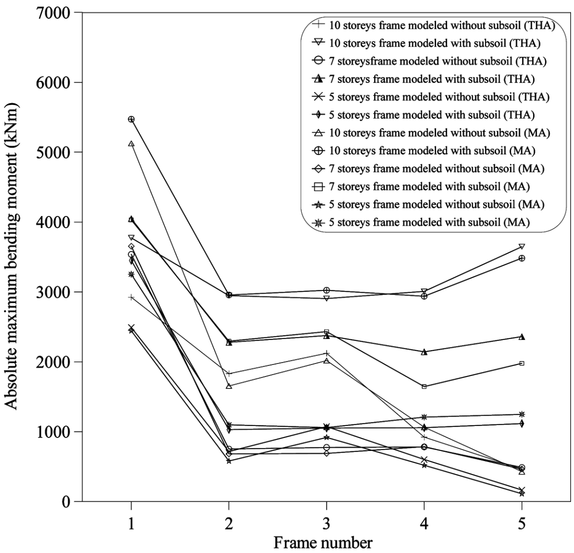


Fig. 5 Absolute maximum bending moments of 3 bays frames

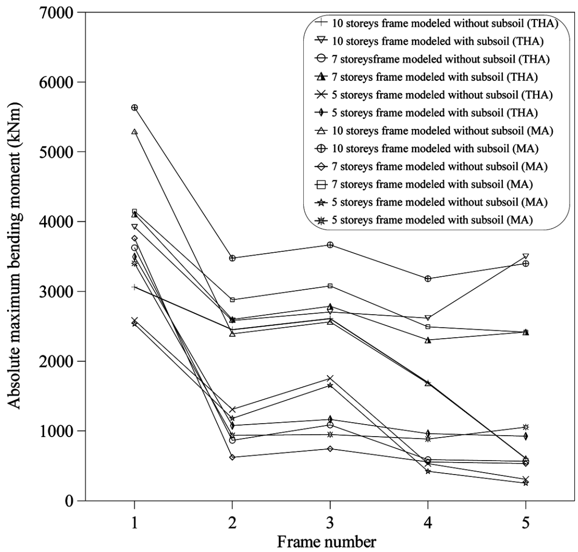


Fig. 6 Absolute maximum bending moments of 4 bays frames

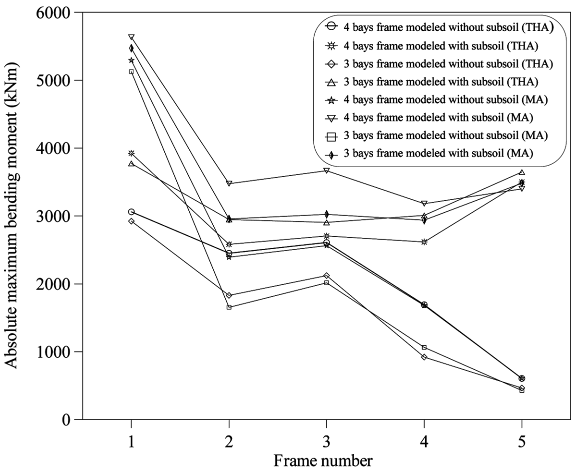


Fig. 7 Absolute maximum bending moments of 10 storeys frames

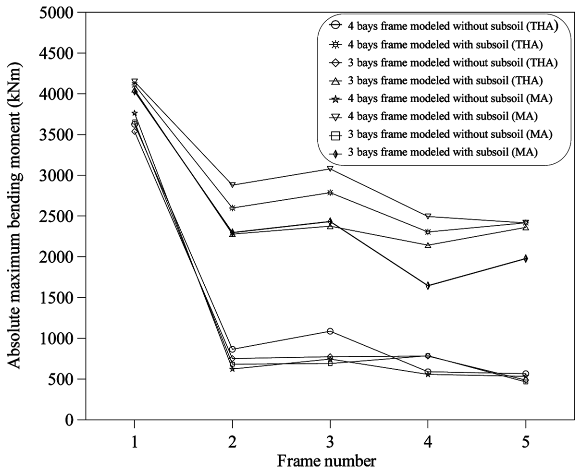


Fig. 8 Absolute maximum bending moments of 7 storeys frames

decreases in the absolute maximum bending moments of 4 bays frame modeled without subsoil for MA, from 10 storeys frame to 5 storeys frames are 52% (from 5293 kNm to 2531 kNm) for the moment-resisting frame, 51% (from 2392 kNm to 1180 kNm) for the frame stiffened with diagonal bracing (frame no: 2), 36% (from 2564 kNm to 1652 kNm) for the frame stiffened with diagonal bracing (frame no: 3), 75% (from 1682 kNm to 421 kNm) for the frame stiffened with X-bracing (frame no: 4), and 59% (from 608 kNm to 251 kNm) for the frame stiffened with shear wall (frame no: 5). In addition, 10 storeys frames have larger absolute maximum bending moments than those of 7and 5 storeys frames and 7 storeys frames have larger absolute maximum bending moments than those of 5 storeys frames, except frames no: 2 and 3 if the subsoil is not taken into

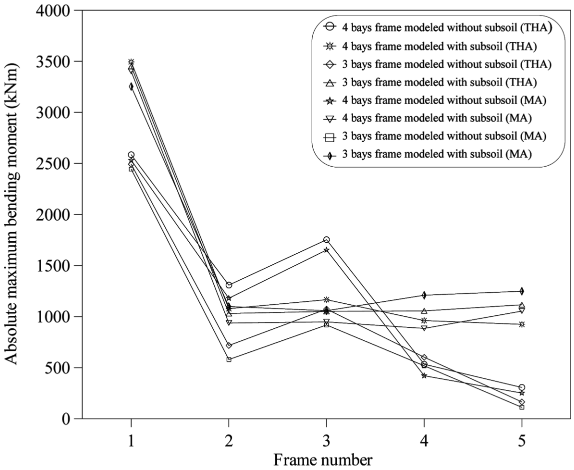


Fig. 9 Absolute maximum bending moments of 5 storeys frames

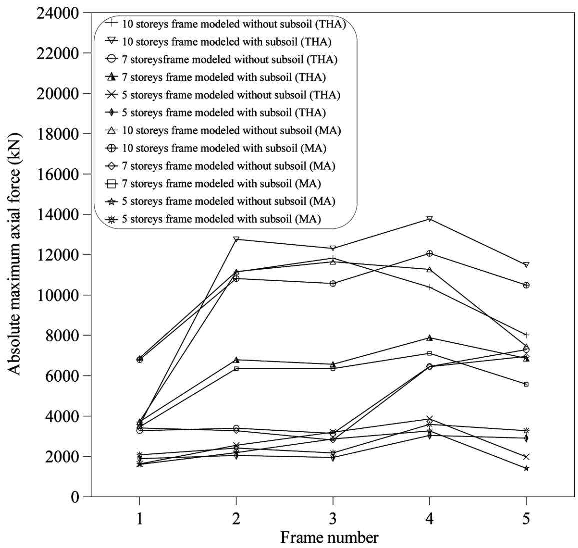


Fig. 10 Absolute maximum axial forces of 3 bays frames

consideration. For each storey number, the largest absolute maximum bending moment occurs at the moment-resisting frames (frame no: 1) and the smallest absolute maximum bending moment occurs at the frames with shear walls (frame no: 5) if subsoil is not considered. If subsoil is considered, the smallest absolute maximum bending moment occurs at the frame with X-bracing (frame no: 4). Among the frames with diagonal bracing, the smallest absolute maximum bending moment occurs at the frame with X-bracing and the largest absolute maximum bending moment occurs at frame no: 3. It can easily be seen that how the configuration of the braces affects the behavior of the frames.

In general, the absolute maximum bending moments of the frames stiffened with shear wall are less than those of the other frames considered if subsoil is not considered. If subsoil is considered, the smallest absolute maximum bending moment occurs at the frame with X-bracing (frame no: 4). The absolute maximum bending moments of the frames modeled with subsoil are larger than those of the frames modeled without subsoil. The difference between the results of these two cases is not negligible from the design point of view. The results of the frames analyzed with THA are very close to the results of the frames analyzed with MA from the absolute maximum bending moment point of view.

As seen from Tables 1, and 2 and Figs. 10, and 11, the largest absolute maximum axial forces occur at the 10 storeys-4 bays frame stiffened with X-bracing modeled without subsoil for MA. The absolute maximum axial forces of 10-storey and 4-bay frames without subsoil increase rapidly from 6795 kN to 15490 kN (128%) if the frame stiffened with X-bracing is used instead of moment-resisting frames. This increase is 125% (from 6795 kN to 15300 kN) for the frame stiffened with diagonal bracing (frame no: 2), 105% (from 6795 kN to 13930 kN) for the frame stiffened with diagonal bracing (frame no: 3), and 52% (from 6795 kN to 10360 kN) for the frame stiffened with shear wall (frame no: 5). The similar trends can also be seen from the same tables and figures for the other frames. The smallest absolute maximum axial force occurs at the moment-resisting frames.

As seen from Figs. 12, 13, and 14, the absolute maximum axial forces of 4 bays frames are generally larger than those of 3 bays frames. If the comparison is made according to the storey

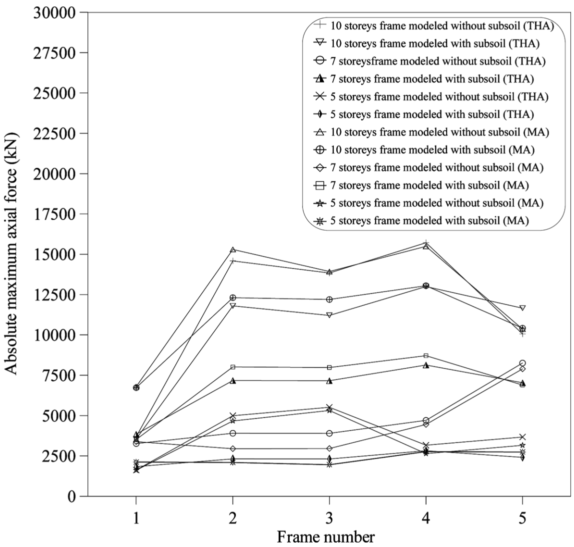


Fig. 11 Absolute maximum axial forces of 4 bays frames

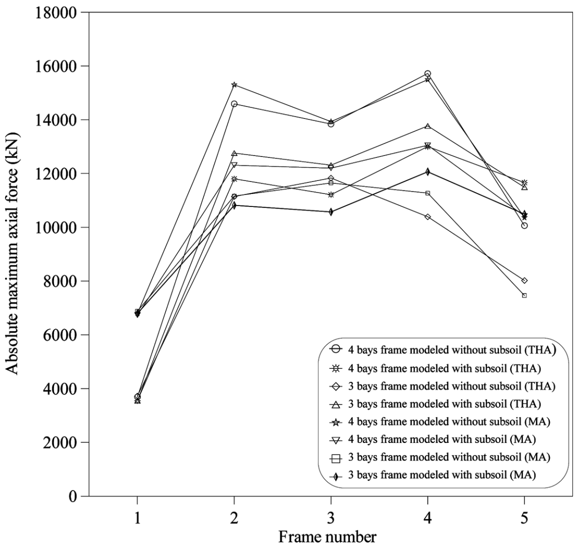


Fig. 12 Absolute maximum axial forces of 10 storeys frames

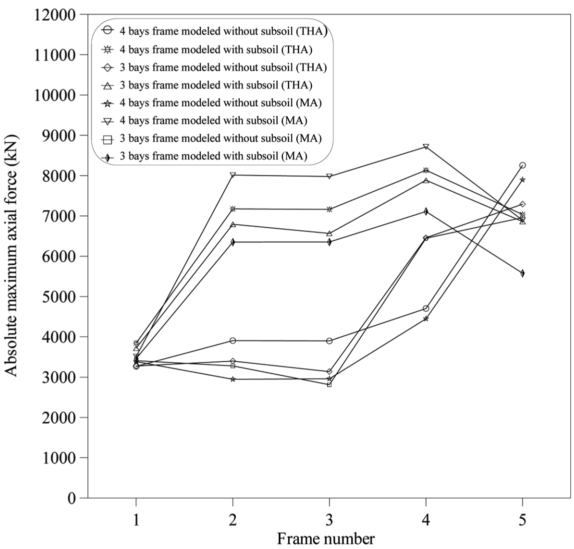


Fig. 13 Absolute maximum axial forces of 7 storeys frames

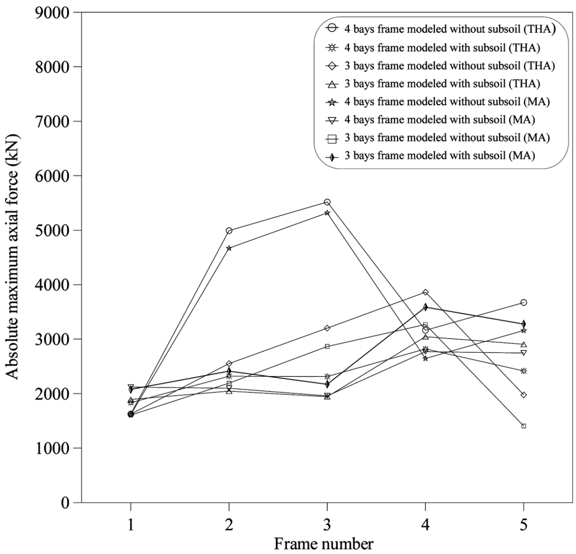


Fig. 14 Absolute maximum axial forces of 5 storeys frames

number, the decreases in the absolute maximum axial forces for 4 bays frames modeled without subsoil for MA from 10 storeys frame to 5 storeys frames are 76% (from 6795 kN to 1613 kN) for the moment-resisting frame, 69% (from 15300 kN to 4669 kN) for the frame stiffened with diagonal bracing (frame no: 2), 62% (from 13930 kN to 5317 kN) for the frame stiffened with diagonal bracing (frame no: 3), 82% (from 15490 kN to 2644 kN) for the frame stiffened with X-bracing, 70% (from 10360 kN to 3158 kN) for the frame stiffened with shear wall (frame no: 5).

In general, the absolute maximum axial forces of the moment-resisting frames are less than those of the frames stiffened with different stiffening members. The absolute maximum axial forces of the frames modeled including subsoil are larger than those of the frames modeled not including subsoil. The differences between the results of these two cases are not negligible from the design point of view. The results of the frames analyzed with THA are very close to the results of the frames analyzed with MA from the absolute maximum axial force point of view. The stiffening members types used in this study induce the axial force from lateral loads and decrease the bending moment at any section of the frame.

It should be noted that the absolute maximum values of the bending moments and axial forces presented above occurred in the columns of the first storey. Furthermore, the absolute maximum bending moments of the frame no: 1, 2, and 4 occurred in the mid columns, but those of frame no: 3 and 5 occurred in the outer column. The absolute maximum axial forces of all the frames occurred in the outer columns.

Another important parameter in the design of the RC frames is the inter-storey drifts. Since presentation of the inter-storey drifts for all frames considered in this study will take up excessive spaces, only the inter-storey drifts of the frame no: 1, and 5 are presented, and these inter-storey drifts are given in Table 3.

As seen from this table, the maximum inter-storey drift occurred to be 0.0722 m on the fourth storey of the 10-storey and 4-bay frame with subsoil for MA. The minimum inter-storey drift occurred to be 0.0007 m on the first storey of the 5-storey and 3-bay frame without subsoil for MA. In general, the inter-storey drifts of the frames modeled with subsoil are larger than those of the frames without subsoil, and the inter-storey drifts of the moment-resisting frame (frame no: 1) are larger than those of the frame stiffened with shear wall (frame no: 5). Although the results of the other frames are not presented in this study as mentioned above, the same trends are also valid for them, i.e. the inter-storey drifts of the stiffened frames are less than those of the moment-resisting frames. Therefore, the braced frames are better than the moment-resisting frames from inter-storey drifts point of view.

3. Conclusions and recommendations

The behavior of reinforced concrete structures subjected to earthquakes changes depending on the dynamic characteristics of the subsoil, structures and earthquake excitations. Therefore, to generalize the results obtained in this study, the responses of the different structures subjected to different earthquakes should be evaluated all together. Therewithal, the following conclusions can be drawn from the results obtained in this study.

The frames stiffened with shear walls (frame no: 5) give better results than the others for all responses obtained in this study, except that 10-storey frame no: 5 modeled with subsoil have larger absolute maximum bending moments than frame no: 4 and that moment-resisting frames have smaller axial forces.

Although the absolute maximum displacements and bending moments of the frames modeled including subsoil are generally larger than those of the frames modeled not including subsoil, the absolute maximum axial forces of the frames modeled including subsoil are generally less than those of the frames modeled not including subsoil.

The stiffening members types used in this study induce the axial force from lateral loads and decrease the bending moment at any section of the frame. This may results with the yielding of

Table 3 The absolute maximum inter-storey drifts (m) of frame no: 1 and frame no: 5

Storey number	Bay number	Storey	Frame no: 1				Frame no: 5			
			With subsoil		Without subsoil		With subsoil		Without subsoil	
			MA	THA	MA	THA	MA	THA	MA	THA
5	3	1	0.0198	0.0217	0.0160	0.0117	0.0064	0.0054	0.0007	0.0014
		2	0.0321	0.0296	0.0252	0.0182	0.0068	0.0058	0.0012	0.0017
		3	0.0334	0.0254	0.0260	0.0188	0.0075	0.0063	0.0015	0.0021
		4	0.0291	0.0194	0.0220	0.0163	0.0077	0.0064	0.0016	0.0022
		5	0.0229	0.0181	0.0166	0.0126	0.0077	0.0066	0.0016	0.0022
	4	1	0.0208	0.0219	0.0165	0.0121	0.0055	0.0040	0.0016	0.0020
		2	0.0331	0.0297	0.0257	0.0185	0.0058	0.0051	0.0027	0.0031
		3	0.0342	0.0254	0.0262	0.0190	0.0063	0.0055	0.0034	0.0039
		4	0.0293	0.0189	0.0220	0.0161	0.0065	0.0056	0.0037	0.0041
		5	0.0226	0.0159	0.0164	0.0123	0.0064	0.0056	0.0036	0.0041
7	3	1	0.0222	0.0195	0.0243	0.0210	0.0091	0.0075	0.0031	0.0049
		2	0.0386	0.0311	0.0397	0.0338	0.0104	0.0100	0.0056	0.0063
		3	0.0424	0.0364	0.0439	0.0362	0.0121	0.0135	0.0075	0.0067
		4	0.0401	0.0372	0.0416	0.0332	0.0132	0.0161	0.0088	0.0068
		5	0.0356	0.0344	0.0356	0.0273	0.0138	0.0175	0.0094	0.0064
		6	0.0304	0.0314	0.0278	0.0204	0.0140	0.0176	0.0096	0.0057
		7	0.0246	0.0281	0.0204	0.0147	0.0140	0.0177	0.0096	0.0049
	4	1	0.0227	0.0188	0.0248	0.0214	0.0119	0.0098	0.0036	0.0038
		2	0.0385	0.0296	0.0402	0.0341	0.0134	0.0114	0.0064	0.0067
		3	0.0419	0.0275	0.0437	0.0363	0.0154	0.0136	0.0086	0.0090
		4	0.0396	0.0371	0.0414	0.0333	0.0166	0.0153	0.0100	0.0104
		5	0.0354	0.0402	0.0352	0.0271	0.0172	0.0166	0.0108	0.0112
		6	0.0299	0.0353	0.0271	0.0202	0.0173	0.0169	0.0110	0.0113
		7	0.0239	0.0286	0.0197	0.0143	0.0172	0.0174	0.0109	0.0112
10	3	1	0.0288	0.0098	0.0343	0.0195	0.0104	0.0104	0.0030	0.0032
		2	0.0582	0.0172	0.0576	0.0323	0.0140	0.0116	0.0056	0.0061
		3	0.0706	0.0399	0.0664	0.0363	0.0184	0.0137	0.0079	0.0085
		4	0.0726	0.0441	0.0674	0.0352	0.0219	0.0156	0.0096	0.0103
		5	0.0691	0.0362	0.0641	0.0314	0.0247	0.0182	0.0109	0.0116
		6	0.0626	0.0274	0.0580	0.0260	0.0266	0.0221	0.0117	0.0125
		7	0.0548	0.0202	0.0502	0.0203	0.0279	0.0265	0.0123	0.0130
		8	0.0463	0.0152	0.0411	0.0232	0.0287	0.0302	0.0144	0.0132
		9	0.0378	0.0133	0.0318	0.0214	0.0298	0.0323	0.0123	0.0131
		10	0.0304	0.0136	0.0239	0.0161	0.0291	0.0333	0.0122	0.0129
	4	1	0.0308	0.0100	0.0351	0.0201	0.0109	0.0094	0.0043	0.0042
		2	0.0593	0.0170	0.0583	0.0330	0.0144	0.0103	0.0080	0.0078
		3	0.0708	0.0406	0.0666	0.0383	0.0186	0.0126	0.0112	0.0108
		4	0.0722	0.0438	0.0672	0.0389	0.0221	0.0148	0.0136	0.0131
		5	0.0682	0.0360	0.0632	0.0364	0.0246	0.0182	0.0154	0.0147
		6	0.0614	0.0272	0.0571	0.0313	0.0265	0.0241	0.0165	0.0156
		7	0.0533	0.0199	0.0490	0.0254	0.0277	0.0305	0.0172	0.0161
		8	0.0446	0.0145	0.0398	0.0189	0.0283	0.0341	0.0174	0.0162
		9	0.0359	0.0118	0.0303	0.0137	0.0285	0.0353	0.0173	0.0160
		10	0.0283	0.0109	0.0223	0.0097	0.0286	0.0358	0.0171	0.0160

columns in compression if not carefully designed.

Degrees of decrease and increase in the responses make the selection of the type of bracing important since they change depending on the type of bracing.

Since the frames with the same type of bracing give different results depending on configuration, the configuration of the bracing members comes out to be an important parameter.

The results of the time history analysis are close to those of the modal analysis, but the differences between the results of these two analyses are generally negligible.

The same study can be carried out including the stability constrains of the braces and columns and the different configuration of braces such as bracing one bay. Also, optimum design of the frames considered here can also be studied using genetic algorithm.

References

Ambrose, J. and Vergun, D. (1985), *Seismic Design of Buildings*, John Wiley and Sons, Inc., New York.

Architectural Inst. of Japan, Steel Committee of Kinki Branch (1995), "Reconnaissance report on damage to steel building structures observed from the 1995 Hyogoken-Nanbu (Hanshin/Awaji) earthquake", *AIJ*, Tokyo, May.

Ayvaz, Y., Doangün, A. and Durmu, A. (1997), "Earthquake Behavior of Frame Structures with Different Stiffening Members", *Proceedings of the 4th International Conference on Civil Engineering,* May.

Ayvaz, Y. and Aydemir, Y. (2000), Comparative Analysis of Earthquake Behavior of Frame Structures with Different Stiffening Members, *Proceedings of Advances in Civil Engineering, 4th International Congress*, Gazimagusa, November.

Celep, Z. and Kumbasar, N. (1993), *Introduction to Earthquake Engineering and Earthquake Resistant Structural Design (Turkish),* Sema Press, Istanbul.

Choi, C.K. and Kim, E.-D. (1985), "Multistory frames under sequential gravity loads", *J. Struct. Eng.*, **111**, 2373-2384.

Choi, C.K., Chung, H.K., Lee, D.-G. and Wilson, E.L. (1992), "Simplified building analysis with sequential dead loads - CFM." *J. Struct. Eng.,* **118**(4), 944-954.

Çavdar, Ö. (2005), *Comparative Analysis of Linear Behavior of Frame Structures Stiffened with K and Knee Types Bracing Members Subjected to Eartquake*, M. Sc. Thesis, Karadeniz Technical University, Turkey, January.

Dowrick, D.J. (1987), *Earthquake Resistant Design*, 2nd Ed., John Wiley and Sons, Inc., New York.

Ersoy, U. and Çıtıpıtıoğlu, E. (1988), *Basic Principles Used in Design and Construction of Tall Buildings (Turkish),* Chamber of Civil Engineers, Izmir.

Fan, F. and Ahmadi, G. (1990), "Floor response spectra for base-isolated multi-storey structures", *Earthq. Eng. Struct.*, **19**, 377-388.

Goncalves, R. (1991), "New stability equation for columns in braced frames", *J. Struct. Eng.*, ASCE, **118**(7), 1853-1870.

Gordon, J.C. (2005), *Development of the Full Height Truss Frame*, M. Sc. Thesis, Georgia Institute of Technology, August.

Jangid, R.S. (1996), "Seismic response of an asymmetric base isolated structure", *Comput. Struct.*, **60**(2), 261-267.

Jayachandran, P. (2004), Tall Buildings: Design and Behavior, *Proceedings of the 7th International Congress on Computational Structures Technology,* Lisbon, Portugal, September.

Kalyanaraman, V., Mahadevan, K. and Thairani, V. (1998), "Core loaded earthquake resistant bracing systems", *J. Constr. Steel. Res*., **46**(1), 437-439.

Kim, H. and Goel, S. (1992), Seismic Evaluation and Upgrading of Braced Frame Structures for Potential Local Failures, *UMCEE 92-24, Dept. of Civil Engineering and Environmental Engineering, Univ. of Michigan*, Ann Arbor, Oct.

Krawinkler, H., Anderson, J.C. and Bertero, V.V. (1996), "Northridge earthquake of January 17, 1994:

Reconnaissance report", -- *Steel Buildings, Earthquake Spectra*, Suppl. C, January.
Newmark, N.M. and Rosenblueth, E. (1971), *Fund. Earth. Eng*., Prentice-Hall, Inc., Englewood Cliffs, NJ.
Osteraas, J. and Krawinkler, H. (1989), "The Mexico earthquake of September 19, 1985 -- behavior of steel buildings", *Earthquake Spectra*, February.
Özdemir, Y.I. and Ayvaz, Y. (2002), Comparative Study of Frame Structure Including Subsoil with Different Stiffening Members Subjected to Earthquakes, *Proceedings of the 4th International Congress on Advanced in Civil Engineering,* Istanbul, September.
Öztürk, H. (2005), *Comparative Analysis of Earthquake Behavior of Frame Structures Stiffened with Diagonally and Eccentrically Located Bracing Members*, M. Sc. Thesis, Karadeniz Technical University, Turkey, March.
Pubal, Z. (1988), *Theory and Calculation of Frame Structures with Stiffening Walls,* Elsevier, Amsterdam.
Reitherman, R. (2005), The Expression of Seismic Design, *Consortium of Universities for Research in Earthquake Engineering*, Richmond, CA.
Remennikov, A. and Walpore, W. (1998), "A note on compression strength reduction factor for a buckled strut in seismic-resisting braced systems", *Eng. Struct.*, **20**(8), 779-782.
Rosenblueth, E. (Editor) (1980), *Design of Earthquake Resistant Structures*, Pentech Press Ltd., London.
Saatcioglu, M. and Humar, J. (2003), "Dynamic analysis of building for earthquake-resistant design", *Can. J. Civil Eng.*, **30**(2), 338-359.
Taskin, B. and Hasgür, Z. (2006), "Monte carlo analysis of earthquake resistant R-C 3D shear wall-frame structures", *Struct. Eng. Mech*., **22**(3), 371-399.
Tremblay, R., Timler, P., Bruneau, M. and Filiatrault, A. (1995), "Performance of steel structures during the 1994 Northridge earthquake", *Can. J. Civil Eng.*, **22**(2), 338-360.
TS500 (2000), *Building Code Requirements for Reinforced Concrete*, Turkish Standards Institution, Ankara.