THE STRUCTURAL DESIGN OF TALL AND SPECIAL BUILDINGS
Struct. Design Tall Spec. Build. (2010)
Published online in Wiley Interscience (www.interscience.wiley.com). **DOI**: 10.1002/tal.587

STUDY THE POSSIBILITY OF SEISMIC COLLISION BETWEEN ADJACENT STRUCTURES: A CASE STUDY OF KARIMKHAN AVENUE IN TEHRAN

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SUMMARY

Studies of the past earthquakes show that seismic collision of structures due to the differences in dynamic characteristics of two adjacent structures has significant role in the destruction of different structures (Pantelides and Ma, 1998, Penzien, 1997) in Iran has high vulnerability to earthquake because it is located on seismic belt. Considering the high importance and large population of Tehran City as the capital of Iran, it is necessary to study the probability of collision between adjacent structures and find an index for determination of collapse type for existing structures. In this paper, a collapse index is defined considering the affecting parameters and some of the structures located in one of the most crowded streets of Tehran City (Karimkhan Zand Street) are studied. The results show that the structures should be retrofitted to avoid collapse due to the collision of adjacent structures during a damaging earthquake. Copyright © 2010 John Wiley & Sons, Ltd.

1. INTRODUCTION

Seismic collision of structures during a damaging earthquake occurs in the structures that do not have enough distance from adjacent structures. This phenomenon applies a force on structure that is several times as the force predicted as earthquake load in seismic provisions and thus, local or global damages will occur in the structure. The main reason of collision phenomenon is the different vibration period of adjacent structures that is caused by difference in dynamic properties (Such as mass, stiffness and height). The higher the difference between vibration shapes, the bigger the probability of seismic collision is. It should be noted that seismic collision has been also observed in structures that do not have enough clearance from adjacent structures or in structures that have enough clearance, but are connected to each other by one or more link members. Many collapses have been observed during the past earthquakes due to seismic collision (Hong *et al.*, 2003). Examples of such collapses are the following:

In 1964 Alaska earthquake, a severe damage occurred due to the collision between 14-storey Westward hotel and an adjacent six-storey structure that had 10-cm. clearance. In 1971 San Fernando earthquake, seismic collision between bridge deck and end walls caused lots of structural damage. In 1985 Mexico City earthquake, about 15% of the total damages in the 330 structures who have had severe damages was due to the seismic collision. In 1989 Loma Prieta earthquake, many seismic collisions were observed in old restricts of San Francisco City. The extent of damages caused by seismic collision was significantly high and since then, seismic collision was introduced as a destructive subject during earthquakes and this phenomenon was presented in seismic provisions (Anagnostopoulos,

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Figure 1. Collapse of the highest storey of continental hotel due to seismic collision

1992, Chau *et al*., 2004, Chouw, 2004). Figure 1 shows the damages occurred in Continental hotel during Mexico City earthquake.

Investigations about the vulnerability to seismic collision and proposing retrofitting techniques for existing structures is necessary for structures located in Iran due to the following reasons:

(1) Iran is located on seismic belt and severe earthquakes occur frequently and cause lots of casualties and damages.
(2) Since the land is expensive in most large cities of Iran, structures are constructed without any clearance from each other, especially before the publication of 2800 seismic code in Iran that requires a specific clearance between the adjacent structures to be considered.
(3) After the publication of Iran seismic provision, construction problems and non-observance of city building rules prevent the observance of adequate clearance between structures.

In the following, it is tried to evaluate the situation of structures in Tehran City from seismic collision point of view using the results of past earthquakes and then, a suitable and applicable damage index is proposed.

2. EVALUATION AND DETERMINATION OF DAMAGE INDEX

In this section, the analysis results of some selected structures that are located in one of the most populated streets of Tehran City are presented. It should be noted that all of the selected structures have the probability of seismic collision. Then, a damage index is introduced and defined to have a quantitative criterion for evaluation of structure vulnerability to seismic collision.

As it was mentioned before, the numerical models are developed on the basis of existing structures in Tehran and the selection of structures is carried out in a way that the selected structures can present the general situation of structures in populated cities. Structural models of moment-resisting frames with 4, 6, 8, 10, 12, 14 and 18 stories with and without bracing next to each other are developed. To obtain the damage index, 268 non-linear time-history analyses are conducted using Izmit earthquake record. To increase the accuracy of analyses and considering the abilities of the software used for the analyses, non-linearity is considered both for the geometry and material behaviour.

In this study, it is tried to collect realistic and accurate data. In the cases where it is not possible to collect accurate data, rational assumptions are made. Initial data such as structure height, storey

DOI: 10.1002/tal

number and placement of structures in the vicinity of each other are collected by visiting the structures and more detailed data such as the density of used materials and height level of stories and lateral load resisting systems (moment resisting with and without bracing) are acquired by structural maps. In the conducted analyses, the height levels of stories for adjacent structures are assumed to be the same. The effect of inequality of storey levels is considered by applying an increasing damage index. Some images of the selected structures in Karimkhan Avenue that are used in this study for modelling and analysis are shown in Figure 2.

The results of some analyses for the selected structures with different heights for different conditions of seismic collision are shown in Figure 3.

Acceleration time-history record of Izmit earthquake that is applied to the models is shown in Figure 4.

Analysis results are then used to propose a proper index for determination of building collapse intensity after a damaging earthquake. Impulse force produce shear force at storey levels and the base shear is equal to the summation of storey shears. Thus, changes in storey shears can be observed implicitly in base shear changes. Since the displacements at roof level of building are high, seismic collision may significantly affect it and thus, the shear at the highest storey level is an important factor. To determine the damage index of each building, the critical storey index is calculated and building destruction type and vulnerability to seismic collision is determined as follows. Damage index for each storey level is defined by Equation 1:

$$DI = d \times S_1 \times S_2 \times S_3 \times \alpha \tag{1}$$

The parameter DI is damage index and the parameter d presents the construction method for providing the clearance between two adjacent structures and applies the effect of distance between adjacent structures in damage index. The distance effect is investigated in many previous studies, such as the research carried out by Kasai *et al.* (1990). According to Kasai, the seismic collision phenomenon could easily be explained by momentum transfer during pounding. During a sinusoidal vibration, the momentum (or velocity) of the system is maximum at zero displacement and the momentum is zero at maximum displacement. However, the momentum still maintains 46% of its maximum value when the displacement is 8/9 of the maximum displacement. Since the pounding force is proportional to the momentum transferred, the separation distance is increased from zero to 8/9 (89%) of the separation needed to avoid pounding, the pounding force might only be reduced by half. Thus, as long as the separation is small enough to cause pounding, the difference in the separation distance does not produce a substantial change in the pounding effect.

The results of these studies show that from the seismic collision damage point of view, even if the distance of structures is just 10% smaller than the allowable distance, there is no difference with the case that there is no distance between structures. Considering the mentioned points and the requirements presented in Iranian 2800 seismic code, this parameter is defined as follows:

(1) Equal to 1 when the size of discontinuity joint is smaller than half of the value required in seismic code or when the clearance is fully filled.
(2) Equal to 0·7 when the discontinuity joint at roof level of lower building is at least equal to the half of the value required in seismic code or when the proper clearance exists but it is filled by rubbish or construction material.
(3) Equal to 0 when the discontinuity joint required by code is satisfied.

The parameter S1 represents the placement condition of a structure toward adjacent structures. Considering the results of studies carried out by Naim *et al*. (Naim, 2001) about a past earthquake, many of the structures that survived after the earthquake have the advantage of being placed between two

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Figure 2. Some views of existing structures in Karimkhan Avenue

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Figure 2. *Continued*

DOI: 10.1002/tal

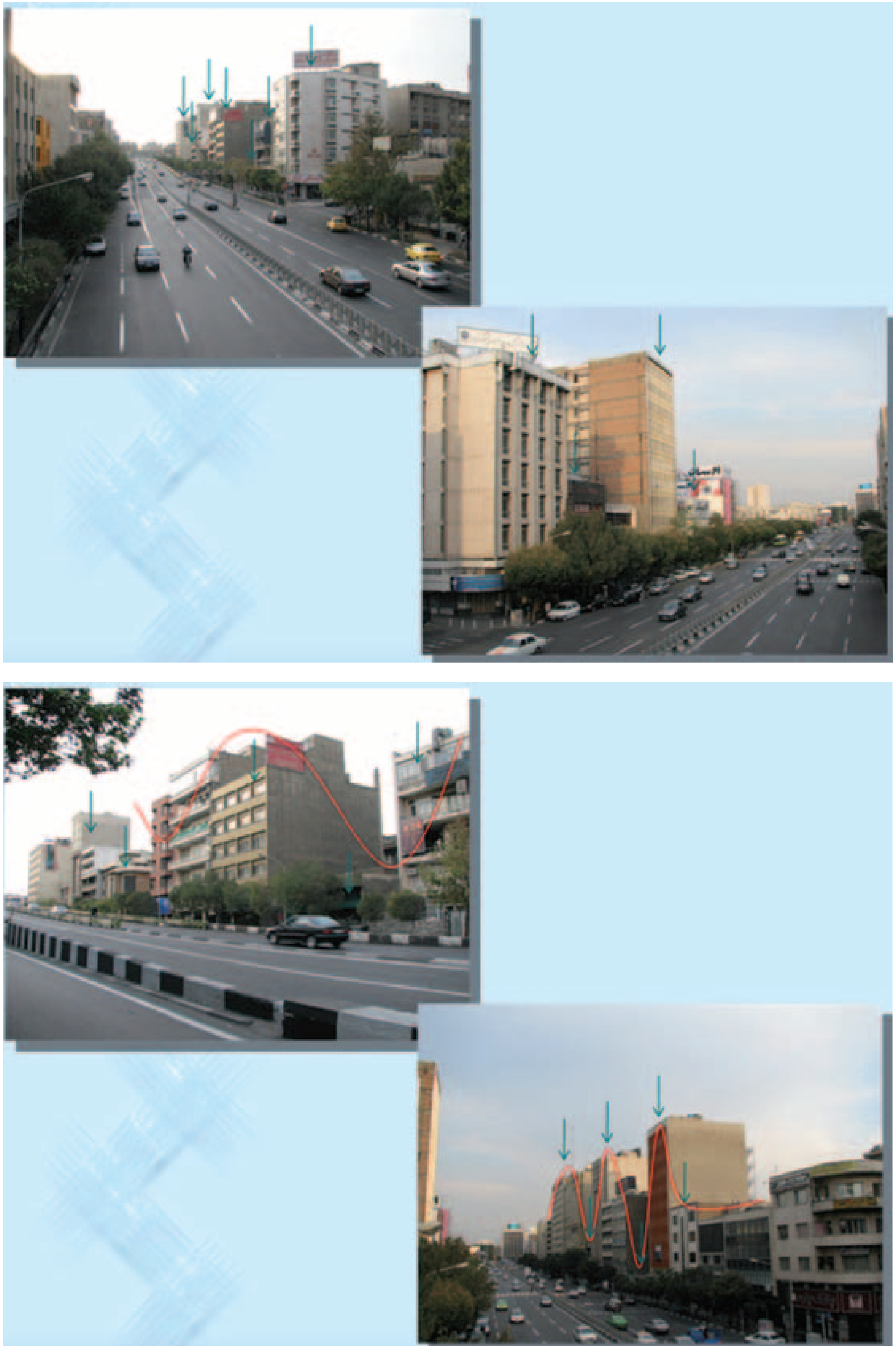

Figure 2. *Continued*

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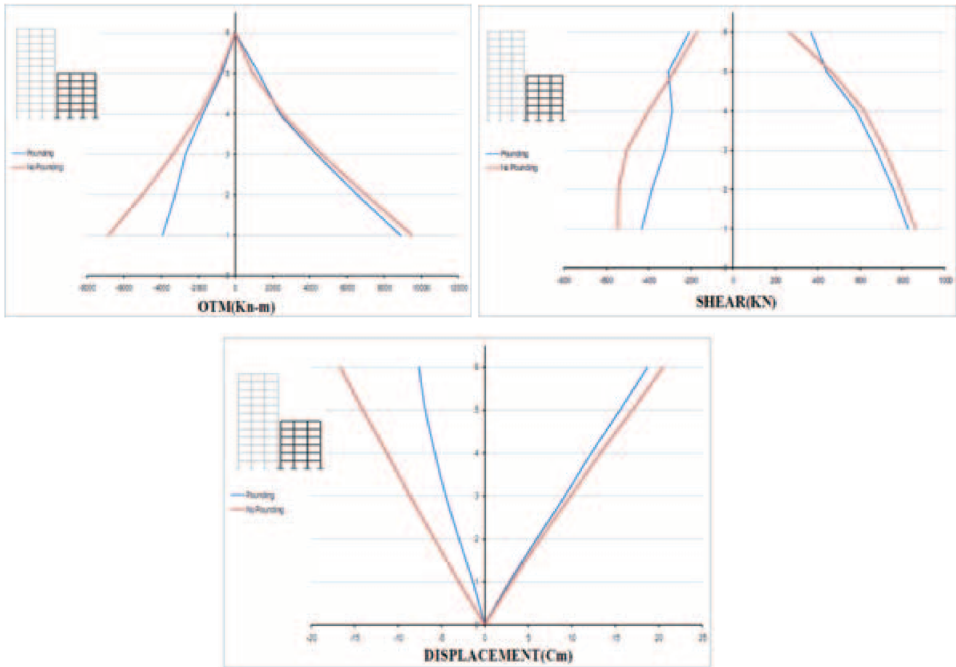
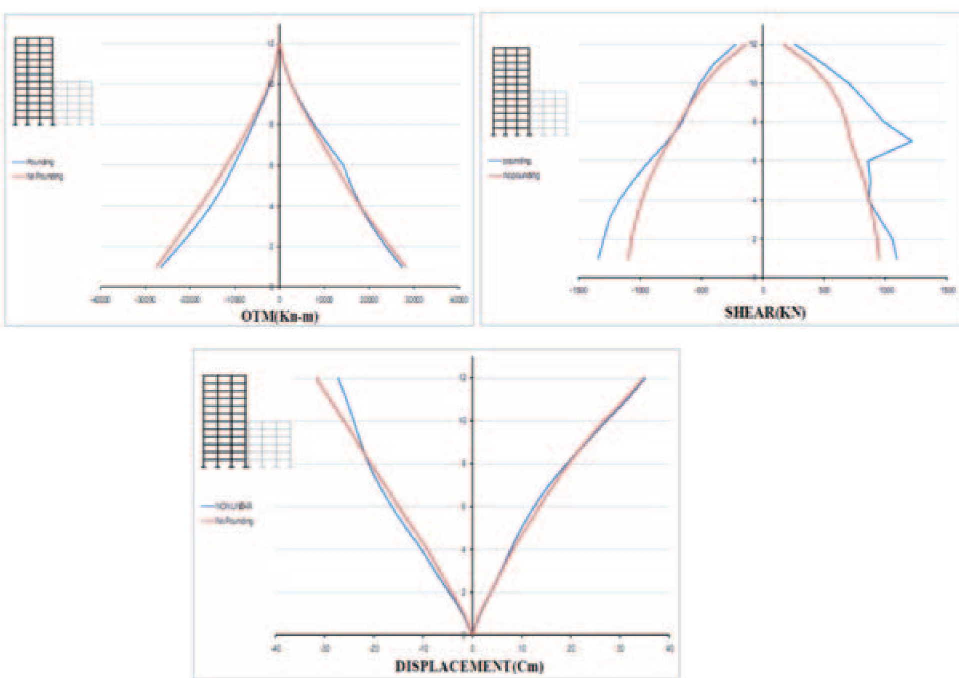


Six-storey



Twelve-storey

Figure 3. Analysis result of some specimens. (a) Analysis results for Short building in the vicinity of tall building (presence or absence of collision)

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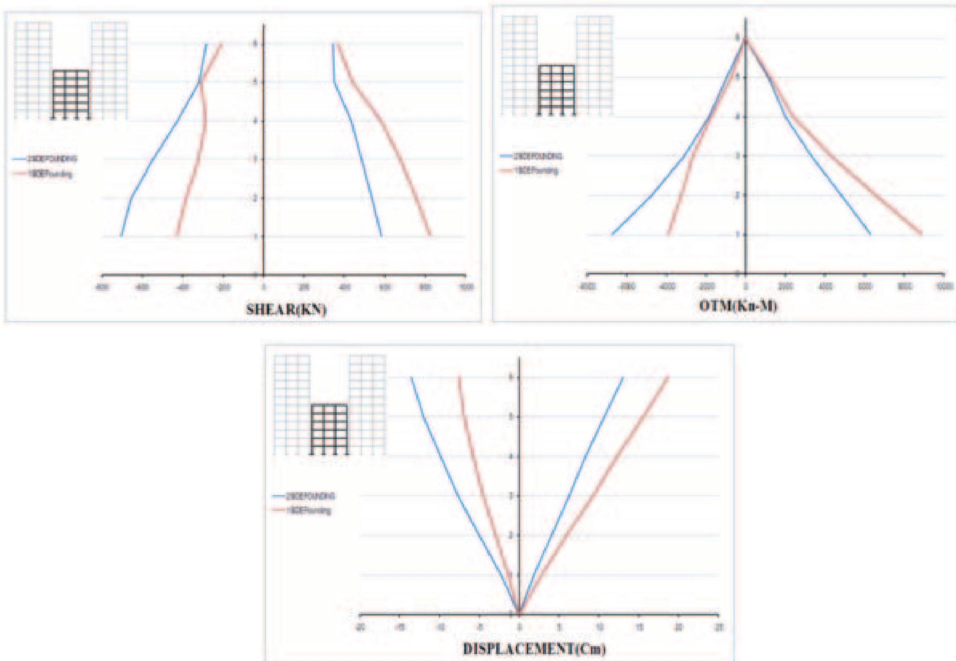

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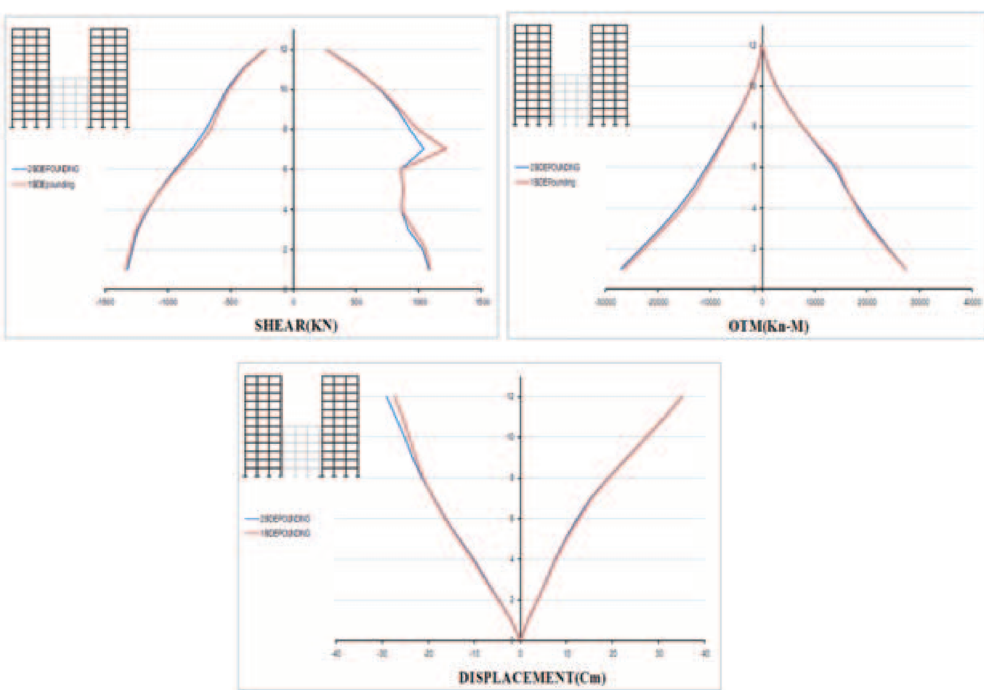

Twelve-storey

Figure 3. (b) Analysis results for Short building in the vicinity of two tall buildings (one way and two way seismic collisions)

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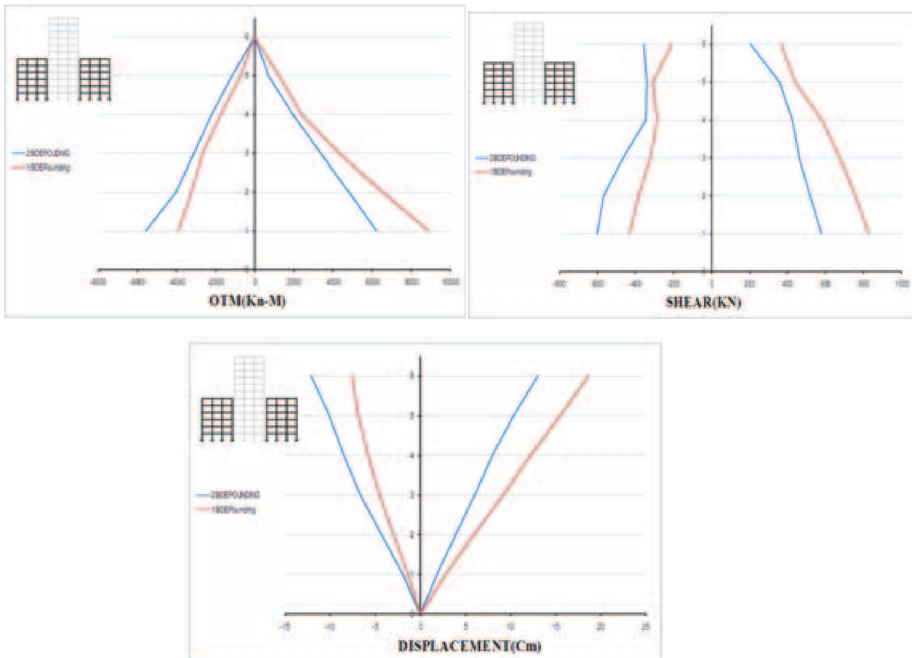
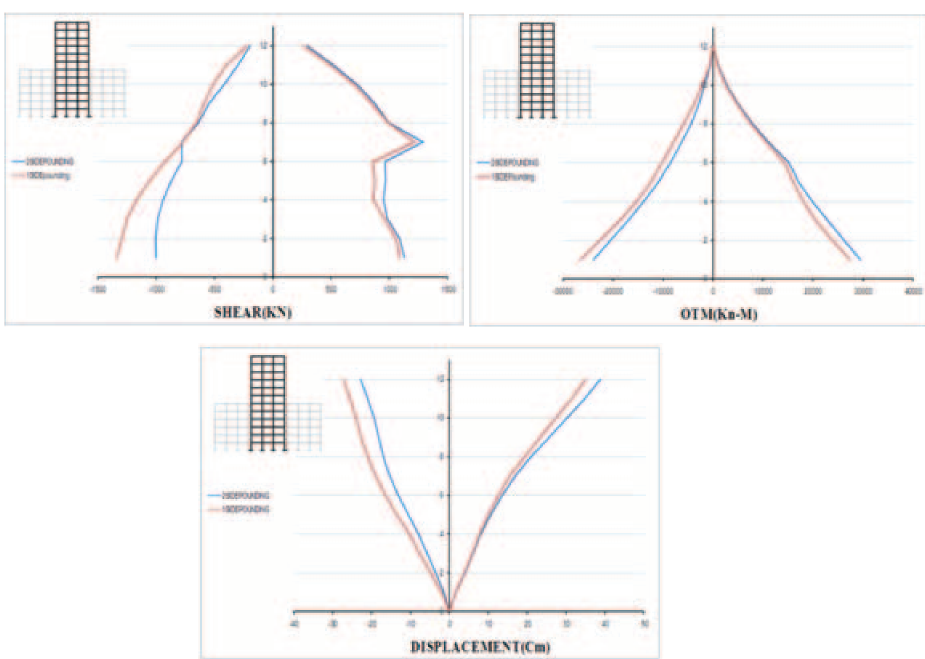


Six-storey



Twelve-storey

Figure 3. (c) Analysis results for High-rise building in vicinity of two short buildings (on-way and two-way seismic collision)

DOI: 10.1002/tal

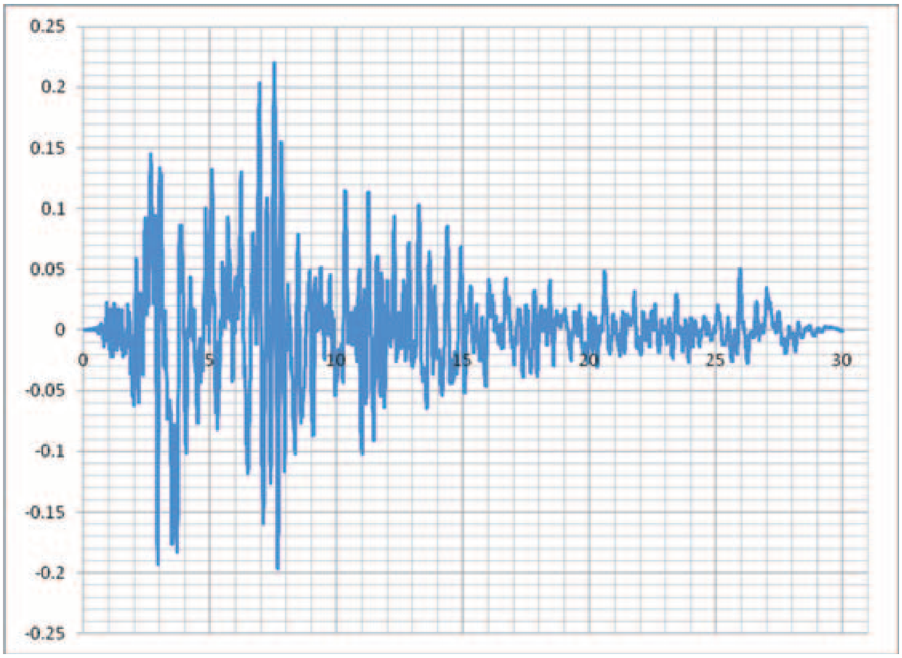


Figure 4. Acceleration time history record of Izmit earthquake

stiff structures from both sides and the structure blocks perform as a unique structure that has better behaviour than those of the separate structure blocks. Furthermore, this can be confirmed in Mexico City earthquake where 42% of the structures severely damaged during the earthquake were corner structures that did not have the support from adjacent structures. The results of current study also show that lower damages are formed in middle structures. Considering the above descriptions, this parameter is defined as follows:

If the structure under study is placed between two other structures (two-way collision), it will be equal to 1 and if the structure is a corner structure (one-way collision), it is assumed to be 1·3.

The parameter S2 represents the inequality of storey heights in adjacent structures at collision level. Moreover, the collision effect of collision between columns is taken into account by this parameter. This kind of collision causes the most severe damages and if the required distance is not observed, the stability elements of structures that are the columns will destroy. Thus, if the storey heights of two adjacent structures are the same, this parameter is equal to 1 and else, it is it equal to 1·5. In the case that the height levels are not equal, but there is a substitute path for load transfer that can preserve the structure stability should the column bend or buckle, this parameter is assumed to be 1 (Figure 5 represent example of such load transferring paths).

The parameter S3 represents the difference in mass and stiffness of two adjacent structures and in the case that the structures are the same (they vibrate in the same phase), it is equal to 1 and else, it is equal to 1·3. Several studies have been conducted in this field, such as the work carried out by Jeng and Tzeng (2000).

In equation 2, α is the base index in critical collision steps which is determined by non-linear time-history analysis carried out on 2D structure models. α_1 is shear amplification coefficient and α_2 is related deformation amplification coefficient and the method for determining these coefficients is presented in Equation 3.

DOI: 10.1002/tal

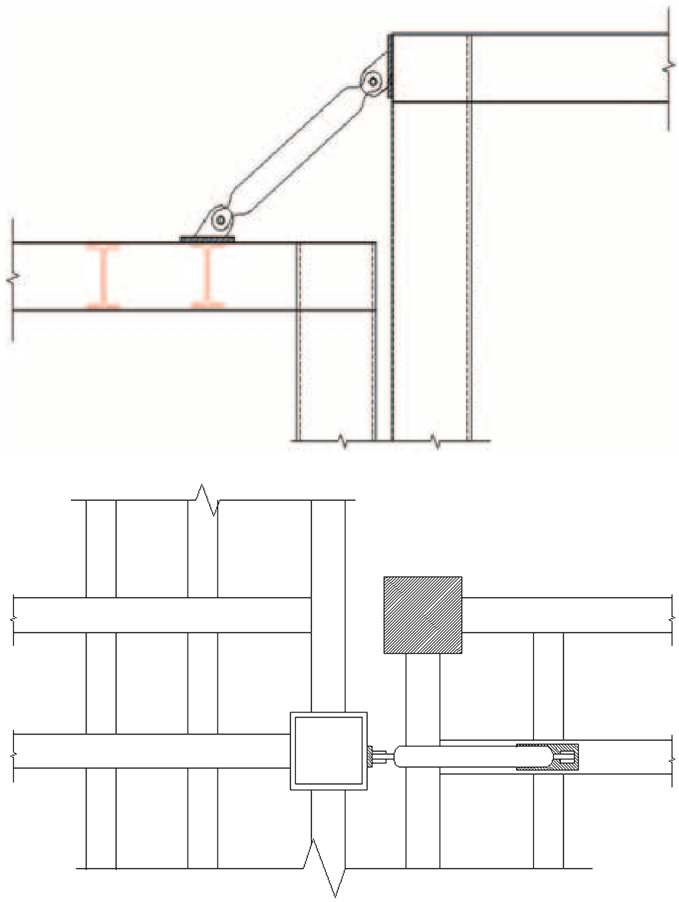


Figure 5. Details of substituting column

$$\alpha = \sqrt{\alpha_1^2 + \alpha_2^2} \tag{2}$$

It should be noted that in the preceding studies carried out about seismic collision, the storey drift effect is not considered. This effect is considered herein by the factor α_2 that increases the accuracy of the equations.

Shear amplification coefficient can be determined by Tables 1–3 and related deformation amplification coefficient can be determined from Tables 4 to 6 for each storey level.

$$\alpha_1 = \frac{\textit{Shear of the storey considering the seismic collision}}{\textit{Shear of the storey without considering the seismic collision}}$$

$$\alpha_2 = \frac{\textit{related deformation of the storey considering the seismic collision}}{\textit{related deformation of the storey without considering the seismic collision}} \tag{3}$$

It should be noted that all above parameters are obtained by statistical study of several conducted analyses in this research.

DOI: 10.1002/tal

Table 1. Amplification factor for base shear (α_1)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	0·99	0·99	1	0·99	0·99	0·92
	6 stories	1·1	1	1	0·99	0·97	0·95	0·93
	8 stories	1·07	1·16	1	1	1·01	0·97	0·95
	10 stories	1·03	1·11	1·09	1	0·99	0·98	0·95
	12 stories	1·11	1·13	1·14	1·12	1	0·99	0·94
	14 stories	1·09	0·99	1·1	1·15	1·19	1	1·02
	18 stories	1·01	0·88	0·92	0·96	1·03	1·02	1
Braced frame	4 stories	1·07	1·85	2·42	2·2	1·51	1·59	1·38
	6 stories	1·01	1·22	1·65	1·21	1	1	0·99
	8 stories	0·99	0·74	1	0·95	0·94	0·91	0·76
	10 stories	1·06	1·1	1·22	1·03	1·21	1·14	1·08
	12 stories	1·01	1·15	1·06	1·02	1·01	1·01	0·99
	14 stories	1	1·04	1·11	0·98	0·94	0·98	0·94
	18 stories	0·97	1·01	1·09	1·06	1·04	1·02	0·81

Lateral load resisting system	Number of stories	Braced adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	0·85	0·86	0·95	0·86	0·87	0·86	0·87
	6 stories	0·95	0·95	0·88	0·91	0·92	0·91	0·9
	8 stories	0·86	1·14	1·02	0·93	0·97	0·92	0·91
	10 stories	0·88	0·92	0·92	1·06	1·1	1·04	0·94
	12 stories	1·03	1·04	1·06	1	0·94	1·19	1·03
	14 stories	1·13	1·2	1·27	1·13	1·04	1·1	1·22
	18 stories	0·87	0·84	0·76	0·77	0·87	0·66	1
Braced frame	4 stories	1	1·13	1·2	1·12	1·53	1·39	1·22
	6 stories	0·91	1	0·83	0·86	0·99	0·97	0·98
	8 stories	0·94	0·8	1	0·76	0·95	0·97	0·74
	10 stories	1·03	1·01	1·16	1	1·01	0·93	0·98
	12 stories	1·1	1·1	1·09	1·02	1	1	0·97
	14 stories	0·95	1·08	1·03	1·01	1	1	0·96
	18 stories	1·01	0·97	0·89	0·83	0·84	1·03	1

Damage index (DI) for each level describes the damage severity at that storey level. The damage severity is classified into five groups as follows:

(1) collapse (DI > 3·1)
(2) severe damage (3·1 > DI > 2·4)
(3) moderate damage (2·4 > DI > 1·9)
(4) little damage (1·9 > DI > 1·4)
(5) no collision (DI = 0)

The mentioned index is only present the probability of damages due to seismic collision and no other seismic damage type is considered.

It should be noted that the levels mentioned in this part are based on the researches of Jeng (1997) and they determined these limits using the past earthquakes that occurred in Taiwan. In this paper, the limits are changed to some extent to be consistent with the earthquakes occurred in Iran. This is conducted using the previous studies and the conducted analyses and considering the seismic condition of Iran.

DOI: 10.1002/tal

Table 2. Amplification factor for final level shear (α_1)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	1·19	1·16	1	0·95	1·1	0·94
	6 stories	1·28	1	1·33	1·33	1·33	1·33	1·23
	8 stories	1·15	1·29	1	1·25	1·32	1	1·34
	10 stories	1·16	1·19	1·15	1	1	1·28	1·32
	12 stories	0·99	0·98	1	1·01	1	1·04	1·26
	14 stories	1·01	0·99	1	1·03	1	1	1·55
	18 stories	1·01	0·93	0·91	0·93	1·17	1·23	1
Braced frame	4 stories	2·09	2·1	2·8	2·7	1·8	1·92	1·8
	6 stories	1·1	1·77	3·17	2·84	2·64	2·37	2·17
	8 stories	1·07	0·95	2·38	2·84	2·89	2·87	3·27
	10 stories	1·08	0·91	1·34	2·5	2·04	2·13	2·23
	12 stories	1	1·03	1·13	1·45	2·14	2·19	2·06
	14 stories	1	1·06	1·08	1·07	1	2·4	2·96
	18 stories	1·01	1·01	0·99	1·03	1·2	0·99	2·43
Lateral load resisting system	**Number of stories**	**Braced adjacent structure**						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1·12	0·87	1·04	0·83	0·68	0·9	1·09
	6 stories	1·27	0·94	0·88	0·94	0·89	0·84	1·22
	8 stories	1·83	1·64	1·09	1·33	1·17	0·76	1·1
	10 stories	1·29	1·55	1·13	1·3	1·31	1·28	0·92
	12 stories	1·24	1·37	1·34	1·46	1·48	1·48	1·12
	14 stories	1·29	1·45	1·51	1·58	1	1·49	1·57
	18 stories	1·2	1·29	1·31	1·45	1·63	1·09	2·05
Braced frame	4 stories	1	2·21	1·66	1·43	2·59	2·85	2·83
	6 stories	1·43	1	1·74	2·21	1·67	2·02	1·92
	8 stories	1·01	1·22	1	2·33	2	2·15	2·38
	10 stories	1·35	1·68	1·95	1	2·3	2·26	2·06
	12 stories	1·05	1·02	1·4	1·49	1	2·35	2·37
	14 stories	1·14	1·19	1·12	1·23	1	1	2·24
	18 stories	1·1	1·24	1·18	1·32	1·4	1·76	1

The main purpose of defining damage index is to evaluate the retrofit need of buildings for prevention of damages produced by seismic collision. Considering the collapse type of critical levels, the structures are classified into 5 groups A to E from the vulnerability to collapse point of view.

Group A: very vulnerable building that is located in collapse threshold (requires serious and comprehensive retrofit)
Group B: vulnerable building that is vulnerable to severe damage due to seismic collision (requires comprehensive retrofit)
Group C: building that is vulnerable to significant damage due to seismic collision (requires local retrofit strategies)
Group D: building that is vulnerable to local damages due to seismic collision (The amount of local damages and their locations and need for retrofit can be just determined by accurate analysis)
Group E: building that is not vulnerable to damage due to seismic collision

The relation between danger levels and damage index is presented in Table 7. Levels A and E represent the maximum and minimum risk value due to seismic collision, respectively.

DOI: 10.1002/tal

Table 3. Amplification factor for collision level shear (α_1)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	1·19	1·16	1	0·95	1·1	0·94
	6 stories	1·08	1	1·33	1·33	1·35	1·3	1·23
	8 stories	1·08	1·29	1	1·25	1·32	1	1·34
	10 stories	1·16	1·35	1·32	1	1	1·28	1·32
	12 stories	1·15	1·51	1·39	1·01	1	1·04	1·26
	14 stories	1·16	1·32	1·56	1·33	1·13	1	1·55
	18 stories	1·04	1·29	1·53	1·62	1·62	1·24	1
Braced frame	4 stories	2·09	2·1	2·8	2·7	1·8	1·92	1·8
	6 stories	1·07	1·77	3·17	2·84	2·64	2·37	2·17
	8 stories	1·05	1·07	2·38	2·84	2·89	2·87	3·27
	10 stories	1·09	1·07	1·46	2·05	2·04	2·13	2·23
	12 stories	1·02	1·06	1·11	1·5	14·2	2·19	2·06
	14 stories	1·04	1·09	1·05	1·05	1·05	4·2	2·96
	18 stories	0·97	1·32	1·41	1·12	0·99	0·98	2·34
Lateral load resisting system	**Number of stories**	**Braced adjacent structure**						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1·12	0·87	1·04	0·83	0·68	0·9	1·09
	6 stories	1·32	0·94	0·88	0·94	0·89	0·84	1·22
	8 stories	1·16	1·62	1·9	1·33	1·17	0·76	1·1
	10 stories	1·32	1·22	1·1	1·03	1·31	1·28	0·92
	12 stories	1·11	1·21	1·13	1·14	1·48	1·48	1·12
	14 stories	1·07	1	1·22	1·18	1·9	1·49	1·57
	18 stories	1·04	1·09	1·02	1·31	1·74	1·82	2·05
Braced frame	4 stories	1	2·21	1·66	1·43	2·59	2·85	2·83
	6 stories	1·47	1	1·74	2·21	1·67	2·02	1·92
	8 stories	1·14	1·29	1	2·33	2	2·15	2·38
	10 stories	1·05	1·73	2·34	1	2·3	2·26	2·06
	12 stories	1·05	1·1	1·36	1·5	1	2·35	2·37
	14 stories	1·12	1·11	1·11	1·1	1·33	1	2·25
	18 stories	1·06	1·03	1·17	1·27	1·42	1·7	1

The result of studies carried out about the 43 selected structures show that 37% of structures undergo very dangerous damages (A) and 27% of them undergo dangerous damages (B). 25% of the structures should be studied more accurately for determination of vulnerability to seismic collision (C) and just 11% of structures will not undergo significant damage (D, E). These investigations can show the practicable evaluation of structures from seismic collision point of view and determine the need of structures for retrofitting against seismic collision.

3. STRATEGIES FOR CONFRONTING WITH SEISMIC COLLISION

3.1 Providing adequate clearance between adjacent structures

As it is observed from the results of the study, the most suitable method for preventing seismic collision is providing adequate clearance between structures (Maison, 1992, Davis, 1992). Some provisions propose the proper distance and necessitate it for structures. The purpose of this section is to examine

DOI: 10.1002/tal

Table 4. Amplification factor for relative deformation at base level (α_2)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	0·96	0·94	0·98	0·91	0·91	0·89
	6 stories	1·05	1	0·96	0·91	0·88	0·84	0·82
	8 stories	0·89	1·03	1	0·88	0·85	0·87	0·85
	10 stories	0·88	1·03	1·01	1	0·86	0·85	0·84
	12 stories	1·03	1·05	1·02	1·08	1	0·95	0·91
	14 stories	0·87	0·98	1·05	1·01	0·98	1	0·81
	18 stories	0·83	0·95	1·07	1·03	0·94	1·07	1
Braced frame	4 stories	0·97	1·05	0·97	0·93	0·97	0·93	0·97
	6 stories	0·96	0·95	0·93	0·97	0·93	0·93	0·97
	8 stories	0·97	1·06	0·97	0·96	0·86	0·91	0·97
	10 stories	0·99	1·06	1·08	0·97	0·95	0·98	0·99
	12 stories	0·97	1·01	1·02	1	0·95	0·97	0·91
	14 stories	1·07	0·95	1·05	1·02	1·09	0·97	0·93
	18 stories	1·04	0·97	1·02	1·04	1	1·03	1·04
Lateral load resisting system	**Number of stories**	**Braced adjacent structure**						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1·05	0·74	0·78	0·72	0·83	0·83	0·83
	6 stories	0·83	1·02	0·77	0·79	0·7	0·79	0·77
	8 stories	0·72	0·78	1·07	0·72	0·72	0·72	0·72
	10 stories	0·76	0·84	0·89	1·05	0·72	0·79	0·74
	12 stories	0·81	0·72	0·87	0·78	1·05	0·79	0·78
	14 stories	0·75	0·77	0·84	0·84	0·78	1·07	0·73
	18 stories	0·72	0·76	0·83	0·86	0·78	0·79	1·05
Braced frame	4 stories	1	0·97	1	0·93	0·97	0·91	0·92
	6 stories	0·81	1	0·9	0·97	0·83	0·83	0·83
	8 stories	0·77	1·03	1	0·91	0·87	0·9	0·81
	10 stories	0·76	1	1·02	1	0·87	0·97	0·87
	12 stories	0·76	1·08	1·07	1·06	1	0·93	0·8
	14 stories	0·79	1·07	1·02	1·01	1·07	1	0·85
	18 stories	0·76	0·98	1·03	1·05	1·02	1·08	1

if the clearance values proposed by Iranian 2800 code is adequate for preventing seismic collision between structures or not. Time-history non-linear analysis is carried out for some selected structures.

To determine the proper distance between adjacent structures, just the moment resisting frames are selected and studied. Each structure model is analyzed using time-history non-linear analysis and displacement of each height level is determined at each 0·005 s intervals. The effect of adjacent structures is often considered and the difference between displacements of two adjacent structures at collision height level is determined at specific time periods and the maximum value is considered as the proper clearance for preventing seismic collision. The results are tabulated in Tables 8–10.

Iran seismic code (2800 code) necessitate the discontinuity joint for the structures whose height is more than 12 meters or the number of stories is more than 4. Each storey of these structures should have a distance from adjacent structure whose value is equal to 1/100 of the height at the storey level. For important structures and for structures that have 8 stories or more, the distance should not be fewer than the product of multiplying design relative displacement by behaviour coefficient R_w. For 4 and

DOI: 10.1002/tal

Table 5. Amplification factor for relative deformation at final level (α_2)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	0·92	0·97	0·96	0·87	0·96	0·88
	6 stories	1·11	1	0·86	1	0·89	0·88	0·78
	8 stories	1·16	1·03	1	0·96	0·92	0·86	0·81
	10 stories	1·09	1·21	1	1	1·03	0·97	0·95
	12 stories	1·08	1·07	1·19	1	1	0·97	1·05
	14 stories	1·2	1·22	1·24	1·17	1·09	1	1·06
	18 stories	1·23	1·27	1·28	1·23	1·21	1·22	1
Braced frame	4 stories	0·96	0·98	1·03	1	1·07	1·03	1·07
	6 stories	0·96	0·97	1	1·03	1·1	1·08	1·1
	8 stories	0·94	1	1·94	1·31	1·26	1·23	1·21
	10 stories	1·11	1	1·23	0·94	1·18	1·15	1·11
	12 stories	1·24	0·94	1·06	1·06	0·95	1·23	1·15
	14 stories	1·43	1·24	1·05	0·91	0·95	0·97	1·1
	18 stories	1·1	1·17	1·17	1·26	1·26	0·88	0·94
Lateral load resisting system	**Number of stories**	**Braced adjacent structure**						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1·07	0·94	0·83	0·87	1·05	0·87	0·83
	6 stories	0·88	1·07	0·85	0·87	0·85	0·87	0·88
	8 stories	1·05	0·97	1·06	0·92	0·84	0·81	0·88
	10 stories	1·35	1·38	1·29	1·07	1·13	1·08	0·95
	12 stories	1·05	1·07	1·34	0·37	1·05	1·14	1·11
	14 stories	1·26	1·22	1·36	1·25	1·3	1·07	1·17
	18 stories	1·28	1·11	1·31	1·17	1·38	1·47	1·07
Braced frame	4 stories	1	1·08	1·1	1·33	1·33	1·47	1·37
	6 stories	1·17	1	1·33	1·17	1·67	1	1·33
	8 stories	1·14	1·14	1	1	1·71	1	1·86
	10 stories	1·29	1	0·87	1	1·33	1·44	1·22
	12 stories	1·34	1·06	1·13	0·85	1	1·27	1
	14 stories	1·3	1·29	1·04	0·84	0·95	1	0·95
	18 stories	1·3	1·39	1·37	1·27	1·27	1·02	1

6-storey structures, the distance from the boundary between adjacent structures was assumed to be 1/100 of structure height. For the structures that have more than 6 stories, the displacement at collision level is determined for each structure and multiplied by half behavior coefficient and the product is assumed as the required displacement between structures. According to the Iranian 2800 code, the required clearance for preventing seismic collision is the summation of distance of each structure from the boundary of two adjacent structures. This clearance is presented in Table 11.

Comparing the results mentioned in Tables 7–10 with Table 11, it can be conclude that satisfying the Iran 2800 code requirement about the minimum clearance between adjacent structures prevents seismic collision and in some cases, this required clearance is conservative and can be reduced by further studies.

It should be noted that some building codes such as FEMA allow the omitting of clearance between adjacent structures, should the seismic collision force is properly considered in structural design procedure. Consequently, a useful method for omitting the clearance is the accurate evaluations of the force produced by seismic collision and thus, retrofit of existing structures without clearance is one of the methods to resist the seismic collision phenomena.

DOI: 10.1002/tal

Table 6. Amplification factor for relative deformation at collision level (α_2)

Lateral load resisting system	Number of stories	Moment-resisting adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1	0·92	0·86	1	0·89	0·88	0·78
	6 stories	1·12	1	0·86	1	0·89	0·88	0·78
	8 stories	0·97	0·89	1	0·96	0·92	0·86	0·81
	10 stories	1·27	1	1·03	1	1·03	0·97	0·95
	12 stories	1·23	0·89	1·16	1·11	1	0·97	1·05
	14 stories	1·33	1·21	1·07	1·07	1	1	1·06
	18 stories	1·08	1·19	1·05	1·21	1·17	0·96	1
Braced frame	4 stories	0·96	0·98	1·03	1	1·07	1·03	1·07
	6 stories	1·18	0·97	1	1·03	1·1	1·08	1·1
	8 stories	1·07	1·86	0·94	1·31	1·26	1·23	1·21
	10 stories	1·05	1·2	0·73	0·94	1·18	1·15	1·11
	12 stories	1·15	1·06	1·13	1·06	0·95	1·23	1·15
	14 stories	1·21	1·18	1	1·05	1	0·97	1·1
	18 stories	1	1·02	1·09	0·89	1·11	0·81	0·94

Lateral load resisting system	Number of stories	Braced adjacent structure						
		4 stories	6 stories	8 stories	10 stories	12 stories	14 stories	18 stories
Moment resisting frame	4 stories	1·07	0·94	0·83	0·87	1·05	0·87	0·83
	6 stories	0·29	1·07	0·85	0·87	0·85	0·87	0·88
	8 stories	1·26	0·93	1·06	0·92	0·84	0·81	0·88
	10 stories	1·1	1·22	1·22	1·07	1·13	1·08	0·95
	12 stories	1·29	1·33	1·35	1·32	1·05	1·14	1·11
	14 stories	1·38	1·24	1·21	1·27	1·25	1·07	1·17
	18 stories	0·95	0·83	0·95	1·32	1·43	1·43	1·07
Braced frame	4 stories	1	1·08	1·1	1·33	1·33	1·47	1·57
	6 stories	1·25	1	1·33	1·17	1·67	1	1·33
	8 stories	1·14	1·14	1	1	1·71	1	1·86
	10 stories	0·97	1	0·9	1	1·33	1·24	1·22
	12 stories	1·02	1·04	0·88	1·05	1	1·27	1
	14 stories	1·14	1·12	1	0·84	0·86	1	0·95
	18 stories	1·07	0·94	0·86	1·05	1·32	1·04	1

Table 7. Classification of structures from seismic collision risk point of view according to damage index of critical stories

Critical stories			Damage index
Roof level	Impulse level	Base level	
B	A	A	DI > 3·1
C	B	A	3·1 > DI > 2·4
D	C	Base Level	2·4 > DI > 1·9
E	D	C	1·9 > DI > 1·4
E	E	D	DI = 0·00

DOI: 10.1002/tal

Table 8. Displacement required between adjacent structures (Time-history non-linear analysis, Izmit earthquake record)

Required distance between structures in centimeters obtained by time-history analysis							
Number of structure stories	4	6	8	10	12	14	18
4	6·24	15·12	16·48	18·45	15·5	14·57	12·54
6	15·12	15·9	18·28	22·75	23·33	24·65	24·47
8	16·48	18·28	12·57	18·96	24·54	25·46	29·55
10	18·45	22·75	18·96	19·3	15·36	25·7	29·49
12	15·5	23·33	24·54	15·36	21	23·2	38·66
14	14·57	24·65	25·46	25·7	23·2	24·02	31·95
18	12·54	24·47	29·55	29·49	38·66	31·95	26·9

Table 9. Displacement required between adjacent structures (Time-history non-linear analysis, Landers earthquake record)

Required distance between structures in centimetres obtained by time-history analysis							
Number of structure stories	4	6	8	10	12	14	18
4	5·27	10·88	17·26	19·79	16·34	13·44	11·09
6	10·8	13·9	16·03	17·47	19·05	20·76	21·8
8	17·26	19·03	10·32	15·47	20·74	23·26	24·5
10	19·79	17·47	15·47	16·54	13·91	19·75	26·05
12	16·34	19·05	20·74	13·91	18·71	22·76	25·05
14	13·44	17·76	23·26	23·75	17·76	21·32	29·14
18	11·09	21·8	22·5	26·05	25·05	29·14	20·72

Table 10. Displacement required between adjacent structures (Time-history non-linear analysis, San Francisco earthquake record)

Required distance between structures in centimetres obtained by time-history analysis							
Number of structure stories	4	6	8	10	12	14	18
4	4·32	11·19	12·52	16·86	12·13	11·04	10·11
6	11·19	14·3	19·58	19·8	21·99	17·88	18·69
8	12·52	13·58	9·51	12	17·5	23·7	25·78
10	16·86	11·8	12	11·54	13·01	17·43	20·58
12	12·13	13·99	17·5	10·01	15·81	19·92	24·11
14	11·04	17·88	23·7	17·43	19·92	22·5	17·93
18	12·11	15·69	18·78	20·58	24·11	17·93	15·8

3.2 Retrofit of existing structures

To clarify the subject, the maximum force produced by seismic collision is calculated for the models using non-linear time history analyses and are presented in Table 12 (maximum force produced in connecting element).

DOI: 10.1002/tal

Table 11. Required clearance between structures (Iran 2800 seismic code)

Required distance between structures in centimetres obtained by time-history analysis							
Number of structure stories	4	6	8	10	12	14	18
4	13·6	17	26·89	626·58	21·89	20·91	19·4
6	17	20·4	40·72	40·48	35·4	32·81	30·33
8	26·89	40·72	79·52	78·82	75·01	72·91	68·36
10	26·58	40·48	78·82	95·27	92·82	91·18	84·74
12	21·89	35·4	75·01	92·82	108·64	107·24	100·35
14	20·91	32·81	72·91	91·18	107·24	121·6	116·31
18	19·4	30·33	68·36	84·74	100·35	116·31	142·38

Table 12. Force produced by seismic collision as a percent of structure mass

Force formed by seismic collision—Moment-resisting frame/structure weight							
Number of Stories	4	6	8	10	12	14	18
4	0·73	2·63	2·39	2·6	2·16	2	1·55
6	2·28	1·1	2·55	2·65	2·26	2·55	2·22
8	1·2	1·91	0·77	1·53	1·32	1·61	1·14
10	0·96	1·67	1·22	0·38	0·8	1·87	0·76
12	0·72	0·61	0·88	0·66	0·68	0·51	1·11
14	0·57	1·09	0·92	1·36	0·44	0·29	1·15
18	0·36	0·74	0·51	0·62	0·74	0·89	0·22
Force formed by seismic collision- Braced frame/ structure weight							
Number of Stories	4	6	8	10	12	14	18
4	0·91	2·82	15	1·67	1·81	2·98	1·89
6	2·83	0·6	0·99	1·32	1·56	2·28	2·53
8	0·75	0·74	0·46	0·84	1·38	1·95	2·08
10	0·67	0·79	0·67	0·33	0·74	0·92	1·01
12	0·6	0·78	0·92	0·62	0·31	0·51	0·93
14	0·85	0·98	1·12	0·72	0·44	0·25	0·56
18	0·42	0·84	0·93	0·56	0·62	0·44	0·3

In addition to the seismic forces mentioned in seismic provisions for earthquake-resistant design of structures, concentrated forces at collision level should be calculated and applied to the structures and the design should be carried out considering all of these forces. The calculated forces can be used for evaluation of structure vulnerability to seismic collision. The seismic collision forces should be applied at the collision level and the weakness of structural members should be determined. In this way, convenient retrofit methods can be proposed for structures.

3.3 Decreasing the collision force using dampers

In this part, the effect of using viscous damper on the force formed by seismic collision and its effect on damage index is studied. Since the connection of adjacent structures at all storey levels is not pos-

DOI: 10.1002/tal

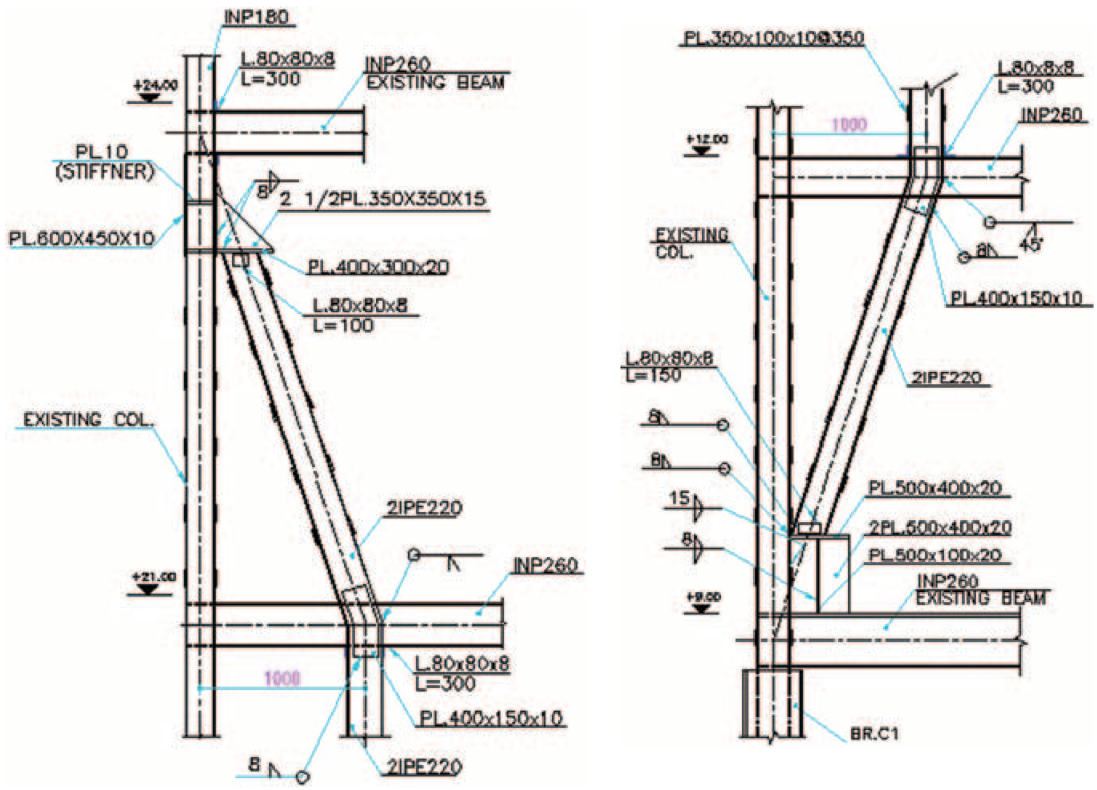


Figure 6. The connection of two buildings by viscous damper

sible, the connection is made at roof level of shorter building. In the next step, the role of damper as a brace member that decreases seismic collision is investigated. The connection detail between two buildings by a viscous damper is shown in Figure 6.

Five pairs of adjacent structures that were found to have the most damage index due to seismic collision are selected. These structures are vulnerable to seismic collision due to the inadequate distance between adjacent structures. Thus, passive viscous dampers are used at roof level of the shorter structure for retrofitting.

The results of analyses are presented in Table 13 for structures without damper and in Table 14 for structures with dampers. As it can be seen, in the majority of structures, the use of damper changed the vulnerability level of structures from severe level to negligible one. In the cases where the seismic collision causes the production of middle column collision, the use of damper transfer the collision level to storey levels.

3.4 Retrofit by substituting column

Connecting two adjacent structures by damper needs the permission of proprietors and also the existence of enough space at roof level. If these conditions do not exist, new retrofitting strategies should be found.

Middle column collision is the most dangerous destruction that may occur due to seismic collision, since the column, the member by which the vertical load is transferring, is directly undergo damage

DOI: 10.1002/tal

Table 13. Analyses results for five pairs of critical structures without damper

Collapse type	DI			d	S3	S2	S1	a*			Moment-resisting frame	Number of stories	Name	No.
	Roof level	Collision level	Base level					Roof level	Collision level	Base level				
A	3·09	3·26	2·06	1	1·3	1	1·3	1·83	1·93	1·22	Braced	6	Tejarat Bank	1
A	3·2	3·2	1·94		1·3	1	1	2·46	2·46	1·49	Shear Wall	4	Pars Mash'al	
A	3·61	4·24	2·61	1	1·3	1	1·3	2·14	2·51	1·54	Braced	10	Mellat Bank	9
A	3·3	3·3	1·54		1·3	1	1	2·54	2·54	1·19	Shear Wall	8	Lyrai Pencil	
B	2·85	2·85	1·59	1	1·3	1	1	2·19	2·19	1·22	Braced	6	Iranshahr Computer	13
A	2·17	3·36	1·7		1·3	1·5	1	1·67	1·72	1·3	Shear Wall	8	Roz System	
B	1·85	2·92	1·8	1	1·3	1·5	1	1·42	1·5	1·39	Braced	8	Medicine	22
C	1·73	1·73	1·6		1·3	1	1	1·33	1·33	1·23	moment resisting frame	4	Tejarat Bank	
C	2·34	2·11	1·81	1	1·3	1	1	1·8	1·62	1·39	Braced	12	Tejarat Bank	31
A	3·15	3·15	1·86		1·3	1	1	2·42	2·42	1·43	Braced	8	Petrochemical inc.	

DOI: 10.1002/tal

Table 14. Analyses results for 5 pairs of critical structures with damper

Collapse type	DI Roof level	DI Collision level	DI Base level	d	S3	S2	S1	a* Roof level	a* Collision level	a* Base level	Moment-resisting frame	Number of stories	Name	No.
B	2·37	2·37	2·3	1	1·3	1	1·3	1·4	1·4	1·34	Braced	6	Tejarat Bank	1
C	1·74	1·74	1·69		1·3	1	1	1·34	1·34	1·3	Shear Wall	4	Pars Mash'al	
A	2·52	2·72	2·62	1	1·3	1	1·3	1·49	1·61	1·55	Braced	10	Mellat Bank	9
D	1·27	1·27	1·33		1·3	1	1	0·98	0·98	1·02	Shear Wall	8	Lyrai Pencil	
C	1·56	1·56	1·76	1	1·3	1	1	1·2	1·2	1·35	Braced	6	Iranshahr Computer	13
C	1·61	1·61	1·72		1·3	1	1	1·24	1·24	1·32	Shear Wall	8	Roz System	
C	1·82	1·82	1·59	1	1·3	1	1	1·4	1·4	1·22	Braced	8	Medicine Information Center	22
C	2·55	2·07	1·66		1·3	1	1	1·24	1·25	1·27	moment resisting frame	4	Tejarat Bank	
C	2·88	2·2	1·66	1	1·3	1	1	1·31	1·33	1·27	Braced	12	Tejarat Bank	
D	1·77	1·57	1·39		1·3	1	1	1·13	1·13	1·07	Braced	8	Petrochemical Inc.	

and loose its functionality. One of retrofit strategies is the use of substitute columns that can transfer vertical loads, should the main columns is collapsed. It should be noted that this method is mentioned in FEMA274 as a retrofit method. The substituting column should be designed in a way that it could be able to transfer vertical loads that are applied due to the destruction of the main columns. Furthermore, it should be noted that if the main column is taking part in lateral load resisting system of the structure, this functionality should be properly transfer to substituting columns or other columns. The substitute column detail is shown in Figure 5.

4. CONCLUSION

The results of parametric studies show that:

(1) Seismic collision of low rise buildings decreases the shear and overturning moment at stories whose height levels are below the collision level and improve the behaviour of structure. However, in the case of high rise buildings, shear and overturning moment are increased significantly, especially at the height level in which the collision is occurring.
(2) Studies carried out about the behaviour of usual steel structures in cities show that the important parameters that differentiate the seismic behaviour and seismic collision behaviour of structures are shear and overturning moment at the collision height level and below it. It is observed that the differences between storey relative deformations are negligible in the two cases, with and without considering seismic collision.
(3) Forty-three case studies carried out on the behaviour of buildings located in one of the most crowded streets of Tehran City show that in 37% of the buildings, extreme damages will occur due to seismic collision during a damaging earthquake (A). high damages will occur in 27% of the buildings (B), 25% of the building should be studied more accurately for determining after collision damages (C) and only 11 % of the buildings do not need more studies and no serious damage will occur during a damaging earthquake (D,E). This results show the need for more studies about seismic collision between adjacent buildings.
(4) When a low-rise building is located between two high-rise buildings, the vibration amplitude of the low-rise building is decreased and its influence on the two adjacent structures is reduced. In this case, the response of high-rise building at the collision level is decreased. Furthermore, the maximum responses in the low rise building are also decreased.
(5) When a high-rise building is located between two low rise buildings, its response is reduced at the height levels below the collision level. At the levels over the collision level, no significant increase is observed in the responses. Like the previous case, the maximum responses of low rise building are decreased.
(6) Connecting two adjacent buildings by dampers will decrease the damage level from severe to negligible. In this way, middle column impulse that is the most dangerous collision type can be transferred to storey levels.

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DOI: 10.1002/tal