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EFFECTS OF STAIRCASE ON THE SEISMIC BEHAVIOR OF RC MOMENT FRAME BUILDINGS

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Abstract
Staircase has a potential to change the seismic behavior of structures, but it is often neglected during design. In this research, effects of staircase in 5 groups including 27 models have been studied. Results show that staircase constructed with the use of RC slab, performs as a K-shaped bracing in longitudinal direction and as an inclined shear wall in transverse direction, so in both directions structural stiffness increases, period and lateral displacement of structure decrease, but staircase constructed by means of stringer beam only acts as a bracing in longitudinal direction. Stiffness caused by small span, inclined RC slabs and perimeter infill walls of staircase, based on the staircase location and the number of structural bays could change mode shape and lead to torsion. Along ladder running, staircase leads shear force and bending moment of columns adjacent to the landing to increase, while the internal forces of others to decrease. The majority of adverse effects of the staircases can be prevented by isolating the staircase from master structure. In this case, only the changes in geometry of the structure due to location and dimension of staircase and arrangement of infill walls should be studied.

Keywords: **Staircase; Seismic Behavior; Reinforced Concrete Frames; Stiffness; Torsion.**

1. INTRODUCTION

Staircase is an architectural element which has high potential to change structural behavior especially moment frames against lateral forces, while it is usually neglected in structural design and it is not included in the model of structure [1, 2, 3, 4, 5, 6]. In fact, what is included in modeling structure of conventional buildings, are beams and columns around the staircase as a void and applied dead and live loads [2, 3, 5]. Due to importance of the staircase in crisis and disasters as a way of escape and rescue routes [1, 2, 4, 6, 7, 8, 9, 10] and maintaining its function after the earthquake, it is necessary to pay special attention to the effects of the staircase in structural analysis and design, in a way that not only does no damage to structures, but also in the event of damage to the structures, this part of building remains intact and in service.

Seismic behavior of staircase in two aspects of its structure and its impact on the master structure can be studied and analyzed. It should be mentioned that the main causes of damage to the staircase are ignoring the staircase in structural design and construction faults including poor quality of landing and stair turret, poor quality of welding and insufficient length of welding in landing beam of steel structures, not using special confining reinforcement over the full height of reinforced concrete columns of landing, and occurring short column. The main aim of this research is to study the effects of staircase on structure in design phase. In the following paragraph, the previous research is briefly reviewed.

Bastami *et al.* studied a steel structure building with two types of structural systems including moment frame and braced frame and six different types of construction details of staircase. The results indicate that the effect of staircase on the period of both structures is negligible. In moment frame, displacement of center of mass and torsional effect in the direction perpendicular to the stringer beam is little, and in the direction parallel to the stringer beam is significant, but in braced frame, depending on the number and cross section of bracings in two directions is less affected by the staircase. In braced frame, staircase has affected only the internal forces of columns adjacent to the landing, but in moment frame, leads to increase the internal forces of these columns and reduce the force of other columns. In their opinion, if the staircase is suspended, modeling the stair can be neglected with acceptable approximation [1]. Results of Bastami *et al.* studies on a reinforced concrete structure with three different types of construction details of staircase have shown that bracing behavior of staircase in longitudinal direction and its inclined shear wall behavior in transverse direction causes the reduction of the natural period of structure and lateral displacement and increase in the stiffness of the structure. By increasing the structure height, effect of staircase on stiffness reduces. Eliminating the staircase from the model of structure is safe for columns and beams away the staircase, but it is unreliable for the ones near the staircase. The behavior model with suspended stair is similar to the models without stair, but stair with this construction detail will be unstable during earthquakes [2]. Singh and Choudhary's studies on two types of geometrical plan configuration with RC structure and on 4 different heights have shown reduction in period of structure, increase in internal forces of landing beams and columns and reduction in inter story drift ratio along two directions of models with staircase [3]. Feng *et al.* analyzed 18 RC structure models. They concluded that in the direction parallel to ladder running the stiffness of structure increases and the story displacement ratio reduces, but in the direction perpendicular to the ladder running effects of staircase on structure can be neglected. Irrational layout of staircase may lead to torsional effect on structure. Staircase increases the internal forces in the members of structure, especially the columns at the location adjacent to the landing platform, where short column formed, while in the frames away the staircase the internal forces are reduced. To avoid the detrimental effects of staircase on structure, they proposed two details for isolating the staircase including full-isolated staircase and semi-isolated staircase [4]. Tegos *et al*. studied five different types of staircases in a model. They concluded that staircase increases the stiffness of the structure, decreases structure's natural period vibration and relative displacements in longitudinal direction and the influence of the vertical component of the earthquake in staircases with a free landing and helical one, is significant [11]. Cao *et al*. reported that the staircase increases the lateral stiffness, story shear and overturning moment and decreases the period, based on the studies along the length of the staircase on two reinforced concrete structures [9]. Alirezaei *et al*. have reported increase in stiffness of structure and torsional effect, reduction in natural period of structure and lateral displacement in the models with staircase especially in direction parallel to the stringer beam, insufficient sections of structural elements around staircase and structural performance enhancement [5]. Hoseini and Jafarnejad's research on two reinforced concrete structure has shown that staircase causes the increase of the stiffness of the structure, base shear and internal force of structural elements around the staircase and reduction of the natural period of structure. Moreover, changing center of rigidity may lead to significant torsional effect [6].

It is obvious that horizontal slab of stair kinks and out of plane bending occurs, but axial force of K-shaped brace elements is transmitted to columns. Also everyone knows that reinforced concrete is different in compression and tension. But this fact does not vary the result of force distribution globally. The main aim of this paper is to show the effect of stair on columns (locally) and structure (globally).

In this study, inclined slab of staircase is not the only variable, it has been attempted to study all effects of staircase on seismic behavior of building, by focusing on the geometry of conventional residential buildings plan in Tehran. Based on carried out investigation, this effects can be categorized into three main groups including increase in stiffness, changes in stiffness distribution and changes in force distribution. Each of them can be the cause of others or affected by other factors. These factors and variables have been studied in many groups which are shown in Fig. 1.

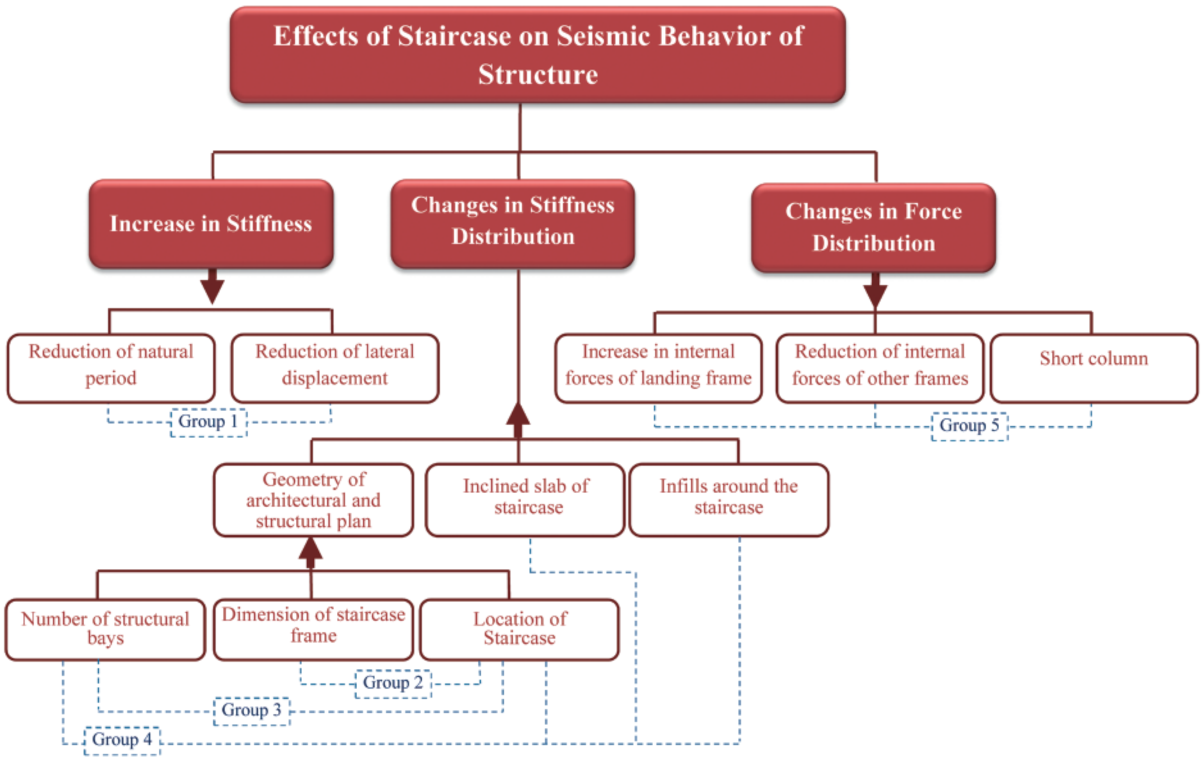

Figure 1.
A chart for effects of staircase on seismic behavior of structure and variables studied in defined groups

2. ARCHITECTURAL AND STRUCTURAL SPECIFICATIONS OF SELECTED BUILDINGS

To study variables quantitatively, three main types of five-story single unit residential buildings in Tehran are selected. In architectural design of multi-unit residential buildings, staircase is usually located in the center of the plan to provide desirable access to all units, so in these buildings, location of staircase does not have significant effects on stiffness distribution. On the contrary, in smaller and single-unit buildings, there are more location for staircase based on the arrangement of interior spaces, natural lighting and circulation. It can be located at corner, middle of length or even middle of width of the building. In this study, buildings with a width of six and ten meters are selected.

In the compact urban layout which is common in most cities of Iran and many other countries, after each two rows of lots, a street is designed and buildings are located on the northern part of the lots. In this way, daylight is available for half of the buildings on the both sides of the north and south, and for the other half, only from the south and there are solid walls on the north side. The first group is called southern building which is located on south of street and the next group is called northern building which is located on north of street. The arrangement of interior spaces and method of natural lighting in the northern buildings is different from the southern ones, so both of them have been studied in this paper. Obviously, the layout of other cities will be subset of this type in term of condition of perimeter walls.

Buildings with a width of 6 meter usually have one structural bay and staircase is located at the corner. In southern lots, entire building is in the form of one-bay structure and only the staircase side is in the form of two-bay structure (Fig. 2). Buildings with a width of 10 meter usually have two structural bays and the most common locations of staircase are at the corner and middle of length (Fig. 3, 4).

Structural system of selected buildings is reinforced concrete intermediate moment resisting frame in two directions, applied forces have been determined based on provisions of the Iranian national building code-part 6 and seismic forces have been calculated based on Iranian seismic code of practice No. 2800 [12, 13]. Concrete and rebar properties are summa-

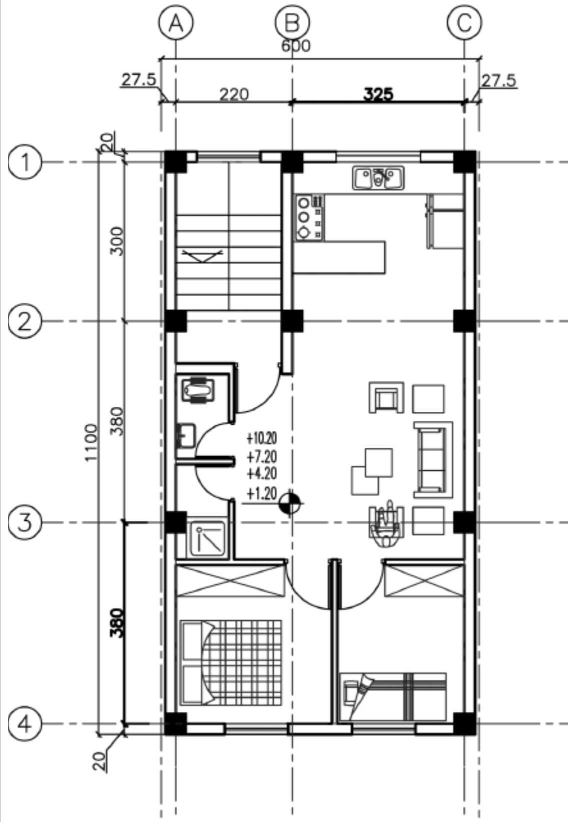

Figure 2.
Architectural plan of southern building with a width of 6 meter and staircase at corner

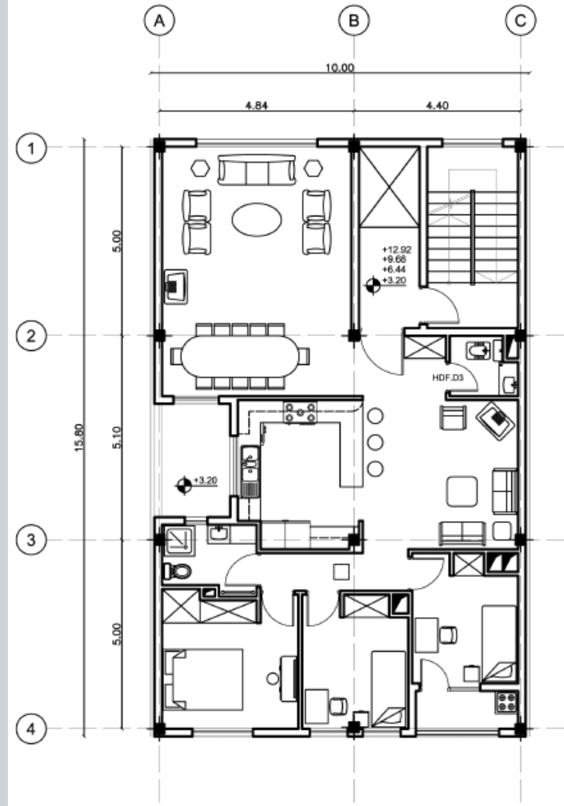

Figure 3.
Architectural plan of southern building with a width of 10 meter and staircase at corner

Table 1.
Concrete and rebar properties

Mass per unit volume kg/m^3	Modulus of Elasticity N/mm^2	Poisson's Ratio -	f'_c Concrete compressive Strength N/mm^2	f_y Bending Reinforcement Yield Stress N/mm^2	f_{ys} Shear Reinforcement Yield Stress N/mm^2
2500	24516	0.15	24.5	392	392

rized in Table 1. Walls have been constructed with 20 cm hollow clay block and staircase with 15 cm thick reinforced concrete slab which is usually integrated with landing beam. Only in group No. 1, staircase is modeled by using beam to compare effects of staircase with beam and staircase with slab. In reinforced concrete buildings, staircase is usually constructed with slab and sometimes by means of joist and block, but in steel buildings, it is always constructed with the use of stringer beam.

According to the purpose of this paper and related variable, such as natural period, distance between center of mass and center of stiffness, drift, torsional effect and distribution of internal forces, using the elastic analysis is appropriate [4]. It is performed by a structural analysis and design software. In modeling, beam-column elements used for beams, columns, and equivalent diagonal strut of infill walls and shell elements for staircases. The connections of all elements except for equivalent diagonal strut of infill walls are rigid.

3. EFFECTS OF STAIRCASE ON SEISMIC BEHAVIOUR OF BUILDINGS

3.1. Increase in stiffness

One of the most important effects of staircase on the building structure is increase in the stiffness [1, 3, 4, 5, 6, 9, 11, 14]. Increasing the stiffness cause a reduc-

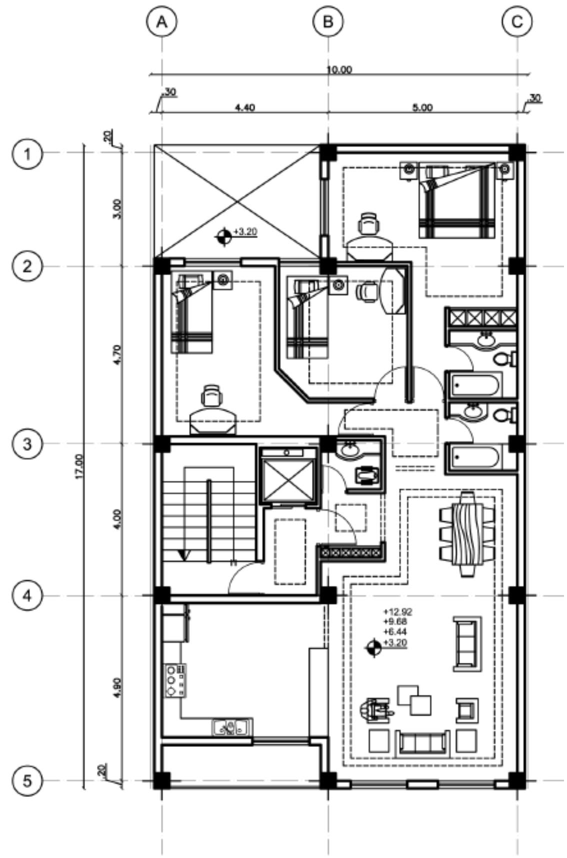

Figure 4.
Architectural plan of northern building with a width of 10 meter and staircase at the middle of length

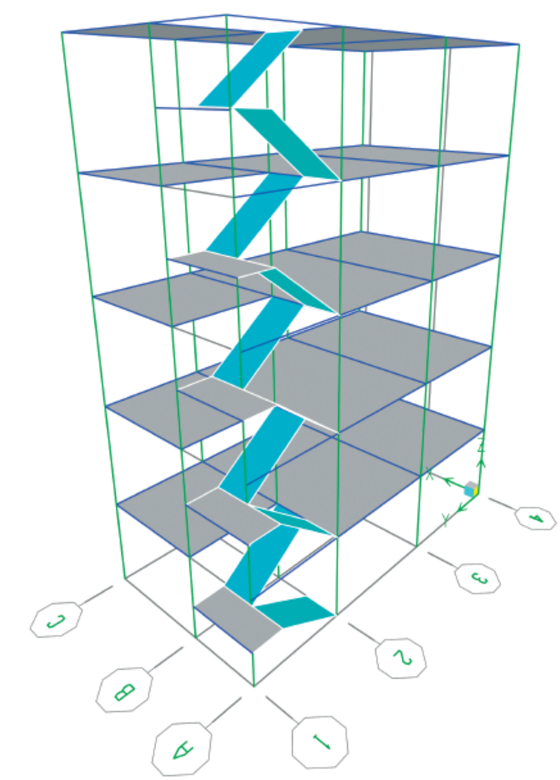

Figure 5.
Model of southern building with a width of 6 meter and staircase slabs

Table 2.
Period and mode shape of southern building with a width of 6 meter

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
Bare frame	0.90	X	69.45	0.00	0.74	Y	0.03	68.82	0.70	T	1.15	1.04
Frame with staircase slabs	0.75	X	46.33	1.73	0.59	Y	14.37	47.47	0.52	T	12.26	24.05
Frame with stringer beams	0.93	X	71.58	0.05	0.72	T	0.29	14.12	0.62	Y	0.00	58.87

tion of the period of structure and lateral displacement and increase of seismic forces. In this paper to compare the stiffness of structure with and without staircase, two factors derived from it including reduction of natural period of structure and story drift ratio are calculated. In previous research, someone has noted to reduction of period and story drift ratio in either direction parallel and perpendicular to the ladder running [2, 3, 10] or increase in the bidirectional lateral stiffness [15], but some others have stated that period and story drift ratio decrease along the staircase and its effect is negligible in transverse direction of staircase [4, 11].

Group 1

In order to evaluate the impact of staircase on reduction of period and drift ratio of structure, southern building with a width of 6 meter is selected and analyzed under three conditions including bare frame, frame with staircase slabs (Fig. 5) and frame with stringer beams. Period of first three modes is presented in Table 2 and drift ratio of two direction of X and Y in Fig. 6, 7. The results show that in the model with staircase slabs, period is reduced by about 16% in X direction and by 20% in Y direction. But, in the model with stringer beams, the reduction of period is negligible in X direction and it is about 16% in Y

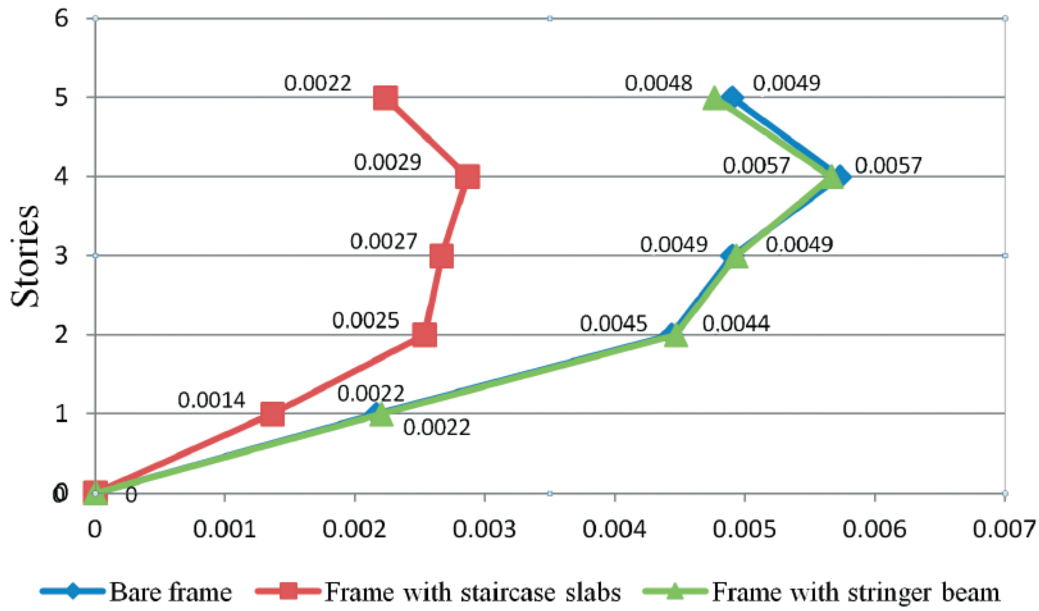

Figure 6.
Drift ratio of southern building with a width of 6 meter in X direction

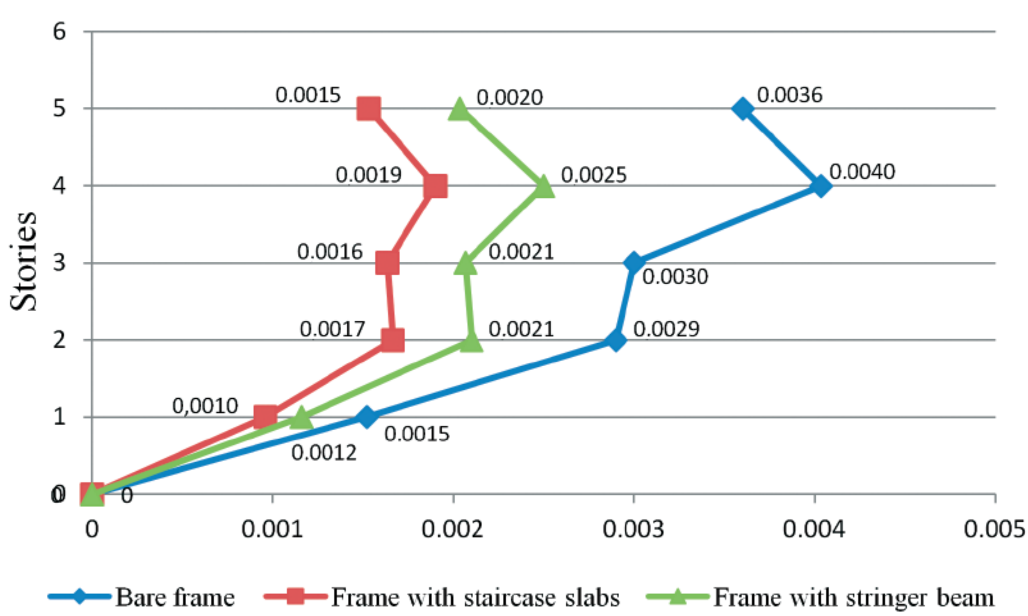

Figure 7.
Drift ratio of southern building with a width of 6 meter in Y direction

direction. In the model with staircase slabs, depending on the stories the drift ratio is reduced from 37% to 57% in both directions. But, in the model with stringer beams, the reduction of drift ratio is not considerable in X direction and it is about 23% to 43% in Y direction. In fact, reinforced concrete slab performs as a K-shaped bracing in longitudinal direction and as an inclined shear wall in transverse direction of staircase and therefore makes fundamental changes in stiffness, period and lateral displacement in both directions. But, stringer beam performs as bracing only in longitudinal direction and its effects in transverse direction is negligible.

3.2. Changes in stiffness distribution

One of the most adverse effects of staircase on the seismic behavior of structure is changes of stiffness distribution and increase in torsion potential. Especially where the staircase is located asymmetrically in building and leads to eccentricity, it is much more important [4, 8, 9, 11, 16]. So, the staircase can change the mode shapes of the structure [11]. In this section, first, the following three main factors which affect the stiffness distribution are discussed, then provisions of seismic codes about torsion as a tool for comparing the results are reviewed and finally the cases in three main groups are modeled to study the variables of this section.

1. Geometry of architectural and structural plan
2. Inclined slab of staircase
3. Infills around the staircase

3.2.1. Geometry of architectural and structural plan

An important part of staircase effects on seismic behavior of structures is related to the geometry of architectural and structural plan. Three main variables including the number of structural bays, dimension of staircase frame and location of staircase in building can be investigated. Since the span of staircase frame is usually shorter than other frames, so stiffness concentration is formed because of shorter length of this beam. This is very important in one-bay structures and especially in moment frames.

3.2.2. Inclined slab of staircase

When the staircase is connected to the structure, it performs as a structural element. Due to inclined form, it acts as a diagonal strut and half-turn landing staircase forms K-shaped bracing (Fig. 8). Because

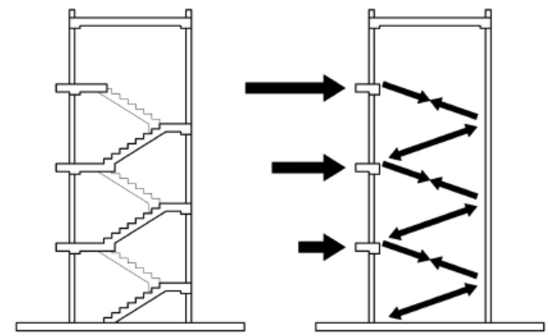

Figure 8.
K-shaped bracing performance of staircase attached to the structure

the stiffness of staircase is more than moment frames, so it could absorb more forces [4, 8] and stiffness concentration in a part of the structure will occur. Since these elements are not considered in structural modeling as usual, so their effects on the structure are not analyzed.

3.2.3. Modelling infills around the staircase

According to fire standards, walls around the staircase should be fire stopping, so they are constructed as 20 cm thick walls. On the other hand, there are structural frames around the staircase, so these walls act as infill walls against lateral forces and lead to concentrating the stiffness in a part of the structure. The stairs, which were usually placed in an eccentric position, often emphasizes the irregular stiffness distribution provided by the position of the infill panels [16].

As it has been attempted to study detrimental effects of staircase on the structure, so simulation is based on macro model. In this method infill walls are modeled with an equivalent compression diagonal strut. Accordingly, the assumptions of a research paper about infill walls with similar material are used. Modulus of elasticity has been assumed 800 times of compressive strength of wall, the effective width of equivalent strut, 0.2 times of wall diameter and thickness of strut, the same as wall. The compressive strength of wall with hollow clay blocks and cement mortar is assumed 3.8 MPa [17]. For considering the effect of opening on the strength and stiffness of walls, Equation 1 recommended by the New Zealand Society for Earthquake Engineering, has been used [18].

$$\lambda_{Opening} = 1 - \frac{1.5\, L_{Opening}}{L_{inf}} \tag{1}$$

Table 3.
Period and mode shape of southern building with a width of 10 meter and staircase at the corner

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
All frames the same	1.01	X	73.76	0.00	0.97	Y	0.01	73.43	0.82	T	0.19	1.04
One different frame	0.97	X	68.80	3.93	0.95	Y	3.42	69.95	0.78	T	2.82	0.39
Two different frames	0.96	X	42.19	31.50	0.94	Y	30.81	43.05	0.78	T	2.81	0.00

Table 4.
Eccentricity of southern building with a width of 10 meter and staircase at the corner

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
All frames the same	4.26	6.61	2.65	6.50	2.32	5.58	1.88	5.01	-1.46	2.28
One different frame	8.26	7.82	5.89	11.70	5.26	14.99	4.29	15.49	0.10	10.68
Two different frames	10.04	7.86	8.38	11.73	8.11	14.89	7.25	15.39	3.06	11.08

Table 5.
Ratio of the maximum relative story drift to the average relative story drift in story 3 of southern building with a width of 10 meter and staircase at the corner

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
All frames the same	1.00	1.11	1.07	1.02	1.06	1.02
One different frame	1.21	1.12	1.30	1.00	1.04	1.02
Two different frames	1.21	1.12	1.29	1.02	1.01	1.05

Table 6.
Period and mode shape of northern building with a width of 10 meter and staircase at the middle of length

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
All frames the same	1.00	X	73.01	0.14	0.90	Y	0.37	68.61	0.79	T	1.03	3.39
One different frame	0.96	X	69.28	2.24	0.91	Y	2.56	72.60	0.77	T	1.37	0.90
Two different frames	0.95	X	72.61	0.63	0.93	Y	0.68	75.46	0.77	T	0.98	0.14

Table 7.
Eccentricity of northern building with a width of 10 meter and staircase at the middle of length

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
All frames the same	2.12	1.23	0.96	3.99	2.54	2.81	3.49	2.02	5.62	2.50
One different frame	2.07	1.28	0.43	4.25	1.79	3.13	2.65	2.36	4.43	2.87
Two different frames	1.74	2.29	-0.80	4.14	0.23	2.57	0.83	1.55	2.31	1.70

Table 8.
Ratio of the maximum relative story drift to the average relative story drift in story 2 of northern building with a width of 10 meter and staircase at the middle of length

	EQX	**EQXP**	**EQXN**	**EQY**	**EQYP**	**EQYN**
All frames the same	1.07	1.04	1.19	1.03	1.02	1.08
One different frame	1.08	1.21	1.03	1.01	1.01	1.06
Two different frames	1.07	1.03	1.19	1.00	1.04	1.04

3.2.4. Provisions of seismic code

According to Iranian seismic code of practice [19], lateral load resisting elements shall be configured in a manner that the torsion resulting from earthquake loading is minimized. For this purpose it is recommended that the eccentricity between the center of mass and center of stiffness, at each floor level, be less than 5% of the building dimension in that level and in the direction under consideration [19]. In this

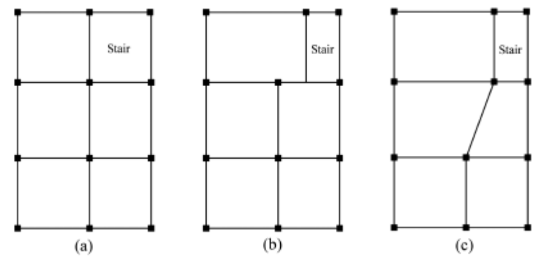

Figure 9.
Southern building with a width of 10 meter; (a) All frames with the same dimension, (b) Frame with shorter length on the landing, (c) Both frames of staircase with shorter length

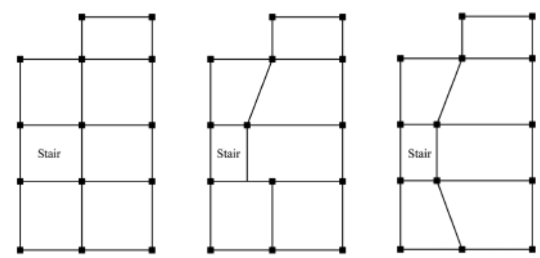

Figure 10.
Northern building with a width of 10 meter; (a) All frames with the same dimension, (b) Frame with shorter length on the landing, (c) Both frames of staircase with shorter length

standard there is no mandatory for the maximum allowable amount of eccentricity. In Australian standard 1170.4–1993, when the distance between center of mass and center of rigidity is in excess of 10% of the structure dimension perpendicular to the direction of earthquake force, torsional irregularity shall be considered but this provision is omitted in new version of 2007 [20, 21]. In Nepal National Building Code about mandatory rules for reinforced concrete buildings with masonry infill walls, the distance between center of mass and center of rigidity including the effects of infill wall shall be less than 10% of building dimension at the same direction [22].

There is another provision in seismic codes to control torsion. According to this, in each story the maximum drift, including accidental torsion, at one end of the structure shall not exceed 20% of the average of the story drift of the two ends of the structure [19, 23, 24, 25].

As shown in Fig. 1, three groups have been defined to study torsional effects of staircase on building structure. In the following, characteristics of each group, outputs of analysis and results are presented. To evaluate torsional effects of each model, mode shapes and two above criteria are used as the main tools. Due to the large amount of outputs of the second criterion, only the results of one story will be presented.

Group 2

In moment frame, due to shorter span of staircase frame, its stiffness is more than other spans, so it absorbs more seismic forces [7]. In this group, to study architectural and structural geometry, two variables including dimension of staircase frame and its location are investigated. To study the location of staircase, two buildings with a width of 10 meter and two-bay structure are selected. In southern building, the staircase is located at the corner and in the northern building it is located at the middle of length. In each of these two plans, three types of structural geometry are selected. In the first type, stairs, elevator and entrance space of each floor are designed in a structural bay, so the entire structure has a regular geometry. In the second type, only the frame dimension of staircase landing is determined based on the staircase dimension. In the third type, dimension of both frames of staircase is determined based on the staircase dimension. The entire structure of three types is in the form of two-bay (Fig. 9, 10). Models of this group are bare frame without inclined slab of staircase. In this group, six models are analyzed.

According to the results, mode shapes of three types of structure in southern building with staircase at the corner are the same and torsion occurs at the third mode of modal analysis. But, in two cases of one shorter frame and two shorter frames, eccentricity along Y axis is greater than 10% of building dimension and the ratios of the maximum relative story drift to the average relative story drift are greater than 1.2 (Table 3 to 5). In the northern building with staircase at the middle of the length, due to proximity of shorter frames to the center of mass, in all three cases torsion occurs at the third mode of modal analysis and eccentricity is less than 10% of building dimension. Only in a few cases the ratios of the maximum relative story drift to the average relative story drift are greater than 1.2. Therefore, torsional irregularity of this building in all structural geometry is very low (Table 6 to 8). Based on the results, when the staircase is located at the corner, even in the absent of staircase inclined slabs and infill walls, structural geometry is prone to torsion alone. Therefore, in this case, the most appropriate geometry of the structure is to design stair, elevator and entrance space in one structural bay and use a uniform geometry in the entire structure. When the staircase is located at the middle of the length, structural geometry has no significant impact and all three types are acceptable. Although using uniform geometry in the structure has its advantages.

Table 9.
Period and mode shape of southern building with a width of 6 meter and staircase at the corner

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
(a) Main structure	0.79	X	60.41	0.30	0.74	Y	0.33	69.75	0.61	T	10.69	0.02
(b) Structure with Hinge connections	0.90	X	69.45	0.00	0.74	Y	0.03	68.82	0.70	T	1.15	1.04
(c) Structure with extra column	0.74	Y	0.07	69.32	0.71	X	69.09	0.07	0.59	T	1.44	0.01
(d) Structure with stronger columns	0.74	X	63.85	2.70	0.73	Y	2.72	67.26	0.59	T	4.00	0.03

Table 10.
Eccentricity of southern building with a width of 6 meter and staircase at the corner

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
(a) Main structure	-0.33	9.29	-0.48	12.37	-0.18	14.08	-0.42	12.65	0.61	10.53
(b) Structure with Hinge connections	-0.33	4.11	-0.48	3.42	-0.15	2.65	-0.33	0.69	0.68	-2.56
(c) Structure with extra column	-0.26	7.42	-0.51	6.89	-0.26	6.55	-1.05	5.98	0.06	5.37
(d) Structure with stronger columns	-0.22	-3.25	-0.42	3.71	-0.15	8.34	-0.20	8.78	0.75	7.22

Table 11.
Ratio of the maximum relative story drift to the average relative story drift in story 3 of southern building with a width of 6 meter and staircase at the corner

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
(a) Main structure	1.26	1.17	1.33	1.01	1.01	1.04
(b) Structure with Hinge connections	1.03	1.12	1.05	1.01	1.02	1.04
(c) Structure with extra column	1.06	1.04	1.13	1.01	1.02	1.03
(d) Structure with stronger columns	1.20	1.09	1.26	1.01	1.01	1.03

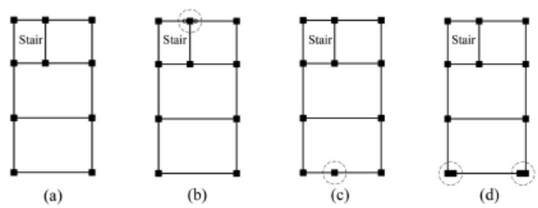

Figure 11.
Southern building with a width of 6 meter; (a) Main moment frame, (b) Hinge connections on the side of staircase, (c) Extra column on the opposite side of the staircase, (d) Columns with larger cross section on the opposite side of the staircase

Group 3

Since the staircase has a significant effect on the one-bay structure [4], in this group to study architectural and structural geometry, worst case of two variable including number of structural bays and location of staircase has been investigated. Accordingly, southern building with a width of 6 meter and staircase at the corner which has one structural bay with the exception of the staircase location is selected. Models of this group are bare frame without inclined slabs of staircase. This group includes four types of structure; main moment frame, hinge connections on the side of staircase, extra column on the opposite side of the staircase, columns with larger cross section on the opposite side of the staircase (Fig. 11).

The results show that torsion in all four types of structure is at the third mode. The distance between center of mass and center of rigidity, only in main structure is greater than 10% of building dimension and the ratios of the maximum relative story drift to the average relative story drift are greater than 1.2 in the main structure and in some cases in the fourth one (Table 9 to 11). Therefore, in one-bay structure with the staircase at the corner, using rigid connection for all structural elements is not allowed. To prevent torsional effects, one of two solutions including hinge connections on the side of staircase or extra column on the opposite side of the staircase will be effective. Using columns with larger cross section on the opposite side of the staircase is not as effective as two other solutions and economically cost effective.

Group 4

This is the main group regarding effective variables on stiffness distribution. In this group number of structural bays and location of staircase as the subset

Table 12.
Period and mode shape of southern building with a width of 6 meter and staircase at the corner

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
(a) Bare frame	0.90	X	69.45	0.00	0.74	Y	0.03	68.82	0.70	T	1.15	1.04
(b) Bare frame with slabs of stair	0.75	X	46.33	1.73	0.59	Y	14.37	47.47	0.52	T	12.26	24.05
(c) Infilled frame	0.75	X	72.73	0.00	0.48	T	0.84	0.72	0.42	Y	0.00	78.42
(d) Infilled frame with slabs of stair	0.60	X	69.86	0.01	0.43	T	4.44	5.72	0.38	Y	0.32	72.76

Table 13.
Eccentricity of southern building with a width of 6 meter and staircase at the corner

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
(a) Bare frame	-0.33	4.11	-0.48	3.42	-0.15	2.65	-0.33	0.69	0.68	-2.56
(b) Bare frame with slabs of stair	-7.05	13.96	-12.17	18.51	-13.03	19.89	-13.98	19.94	-14.09	18.70
(c) Infilled frame	-0.37	-0.08	-0.44	-0.04	-0.07	-1.22	0.51	-2.87	2.17	-5.76
(d) Infilled frame with slabs of stair	-4.35	9.58	-6.84	13.87	-6.57	14.71	-5.78	14.18	-3.89	12.24

Table 14.
Ratio of the maximum relative story drift to the average relative story drift in story 3 of southern building with a width of 6 meter and staircase at the corner

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
(a) Bare frame	1.03	1.12	1.05	1.01	1.02	1.04
(b) Bare frame with slabs of stair	1.43	1.33	1.52	1.12	1.20	1.10
(c) Infilled frame	1.07	1.12	1.01	1.04	1.04	1.08
(d) Infilled frame with slabs of stair	1.20	1.14	1.25	1.05	1.15	1.00

of the main variable of architectural and structural geometry and two other variables including inclined slab of staircase and infills around the staircase are studied. All three selected building in the form of one-bay and two-bay structure with staircase at the corner and middle of the length are analyzed. In the buildings with a width of 10 meter, the case in which all frames have the same dimension and in the southern building with a width of 6 meter, the case in which the structure has hinge connection on the side of staircase are selected. To study inclined slab of staircase and infills around the staircase, four cases including bare frame, bare frame with inclined slabs of staircase, infilled frame and infilled frame with inclined slabs of staircase are modeled. There are 12 models in this group.

According to the results of the southern building with a width of 6 meter, in the cases with infills, torsion occurs at the second mode. The distance between center of mass and center of rigidity, in the cases with inclined slabs of staircase is greater than 10% and also the ratios of the maximum relative story drift to the average relative story drift are greater than 1.2. In these models due to plan geometry, infills balance the concentration of stiffness caused by inclined slabs of staircase (Table 12 to 14). In the southern building with a width of 10 meter, torsion is at the second mode in cases with infilled frames. The distance between center of mass and center of rigidity, in all cases with the exception of bare frame is greater than 10% and the ratios of the maximum relative story drift to the average relative story drift are greater than 1.2 in the models with inclined slabs of staircase (Table 15 to 17). In the northern building with a width of 10 meter, for all models torsion occurs at the third mode and eccentricity is less than 10%. Only in the models with infills the ratios of the maximum relative story drift to the average relative story drift for seismic force along X direction with negative eccentricity are greater than 1.2. In this case where the staircase is located at the middle of length, torsional effects are less than others (Table 18 to 20).

Table 15.
Period and mode shape of southern building with a width of 10 meter and staircase at the corner

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
(a) Bare frame	1.01	X	73.76	0.00	0.97	Y	0.01	73.43	0.82	T	0.19	1.04
(b) Bare frame with slabs of stair	0.92	X	61.95	3.17	0.83	Y	8.78	57.92	0.69	T	4.47	15.91
(c) Infilled frame	0.89	X	74.93	0.00	0.62	T	1.36	3.37	0.59	Y	0.05	77.04
(d) Infilled frame with slabs of stair	0.84	X	71.22	0.08	0.59	T	4.24	26.98	0.53	Y	1.22	53.69

Table 16.
Eccentricity of southern building with a width of 10 meter and staircase at the corner

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
(a) Bare frame	4.26	6.61	2.65	6.50	2.32	5.58	1.88	5.01	-1.46	2.28
(b) Bare frame with slabs of stair	10.70	11.64	13.24	12.40	15.63	12.62	17.38	12.92	17.27	11.12
(c) Infilled frame	4.03	9.49	2.51	11.47	4.52	12.57	6.19	13.48	6.02	12.48
(d) Infilled frame with slabs of stair	7.52	13.47	7.41	15.65	9.66	16.93	11.37	17.83	11.19	16.67

Table 17.
Ratio of the maximum relative story drift to the average relative story drift in story 3 of southern building with a width of 10 meter and staircase at the corner

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
(a) Bare frame	1.00	1.11	1.07	1.02	1.06	1.02
(b) Bare frame with slabs of stair	1.14	1.06	1.24	1.15	1.09	1.18
(c) Infilled frame	1.12	1.06	1.18	1.00	1.02	1.10
(d) Infilled frame with slabs of stair	1.19	1.12	1.25	1.12	1.05	1.21

Table 18.
Period and mode shape of northern building with a width of 10 meter and staircase at the middle of length

	Mode 1				Mode 2				Mode 3			
	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY	Period (s)	Dir.	UX	UY
(a) Bare frame	1.00	X	73.01	0.14	0.90	Y	0.37	68.61	0.79	T	1.03	3.39
(b) Bare frame with slabs of stair	0.87	X	73.39	0.03	0.81	Y	0.83	50.39	0.74	T	1.04	23.82
(c) Infilled frame	0.76	X	72.82	0.05	0.57	Y	1.29	63.40	0.53	T	3.28	15.78
(d) Infilled frame with slabs of stair	0.71	X	72.25	0.00	0.53	Y	0.30	74.46	0.52	T	4.53	5.22

Table 19.
Eccentricity of northern building with a width of 10 meter and staircase at the middle of length

	Story 1		Story 2		Story 3		Story 4		Story 5	
	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey	%ex	%ey
(a) Bare frame	2.12	1.23	0.96	3.99	2.54	2.81	3.49	2.02	5.62	2.50
(b) Bare frame with slabs of stair	-1.86	-0.21	-6.00	2.87	-6.97	1.83	-7.82	1.09	-8.07	1.43
(c) Infilled frame	2.36	3.28	1.59	7.73	2.95	8.11	3.67	8.47	5.71	10.22
(d) Infilled frame with slabs of stair	0.15	2.01	-1.87	6.67	-1.06	7.08	-0.59	7.45	1.21	9.14

Table 20.
Ratio of the maximum relative story drift to the average relative story drift in story 3 of northern building with a width of 10 meter and staircase at the middle of length

	EQX	EQXP	EQXN	EQY	EQYP	EQYN
(a) Bare frame	1.05	1.08	1.18	1.05	1.00	1.09
(b) Bare frame with slabs of stair	1.03	1.12	1.18	1.09	1.13	1.03
(c) Infilled frame	1.17	1.08	1.29	1.07	0.98	1.16
(d) Infilled frame with slabs of stair	1.18	1.08	1.27	0.98	1.05	1.07

3.3. Changes in force distribution

Due to increase of local stiffness in structure caused by staircase, the distribution of internal forces including shear forces and bending moments of structural elements are changed fundamentally. In the columns adjacent to staircase and landing beams, shear force and bending moment increase enormously [1, 2, 3, 5, 6, 10, 15]. Instead, forces of other members decrease [1, 2, 5]. Because structural elements around the staircase do not have enough capacity against applied lateral forces, these regions of structure will fail during earthquakes. Nonlinear analysis also confirms this result. First, the gangplanks in ground floor suffer tension failure, then others in upper floor fail one by one and finally columns of stair and ladder beams fail [4].

Another problem related to the columns located in the staircase landing is short column, becoming weakness of the structure [3, 4, 6, 11, 14, 16]. The short columns especially in reinforced concrete structures can lead to a brittle shear failure [3], but in steel structures will not lead to the failure. Due to force concentration at the middle of landing columns, these columns in reinforced concrete buildings shall be provided with special confining reinforcement over their full height to prevent shear failure [7, 9]. Short column in direction parallel to ladder running is often neglected in structural design, but it is considered in direction perpendicular to ladder running, because of landing beam which is modeled in structural design.

Group 5

To study impact of staircase on lateral force distribution, southern building with a width of 6 meter is selected. Diagrams of shear forces and bending moments under seismic force along Y direction are drawn in both cases with and without inclined slab of staircase (Fig. 12, 13). It has been observed that with incorporation of staircase slab, in columns touching landing beam, shear forces increase about 1.2–3 times and bending moments about 1.1–1.6 times than the model without staircase slab. This is over the capacity of the columns in many parts of structure and will lead to failure. In other columns shear forces decrease about 0.03–0.7 times and bending moments about 0.1–0.7 times than the model without staircase slab. Diagrams of shear forces and bending moments under seismic force along X direction are drawn in both cases with and without inclined slab of staircase (Fig. 14, 15). Because an inclined slab of staircase performs as shear wall in transverse direction, internal forces and moments in all structural elements will reduce. It should be noted that if the staircase is constructed with stringer beams, its effects in longitudinal direction is similar to the staircase constructed with inclined slab and in transverse direction is similar to bare frame and has no significant effects.

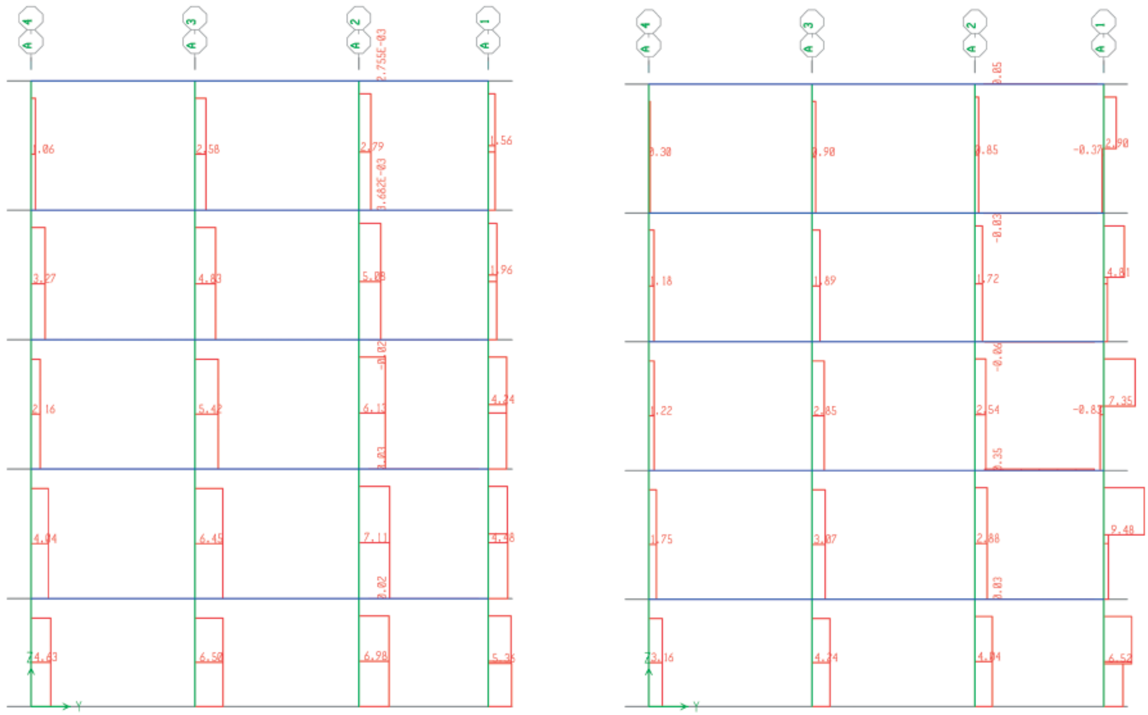

Figure 12.
Shear distribution under seismic force along Y direction (ton): (Left side) Model without stair case, (Right side) Model with staircase

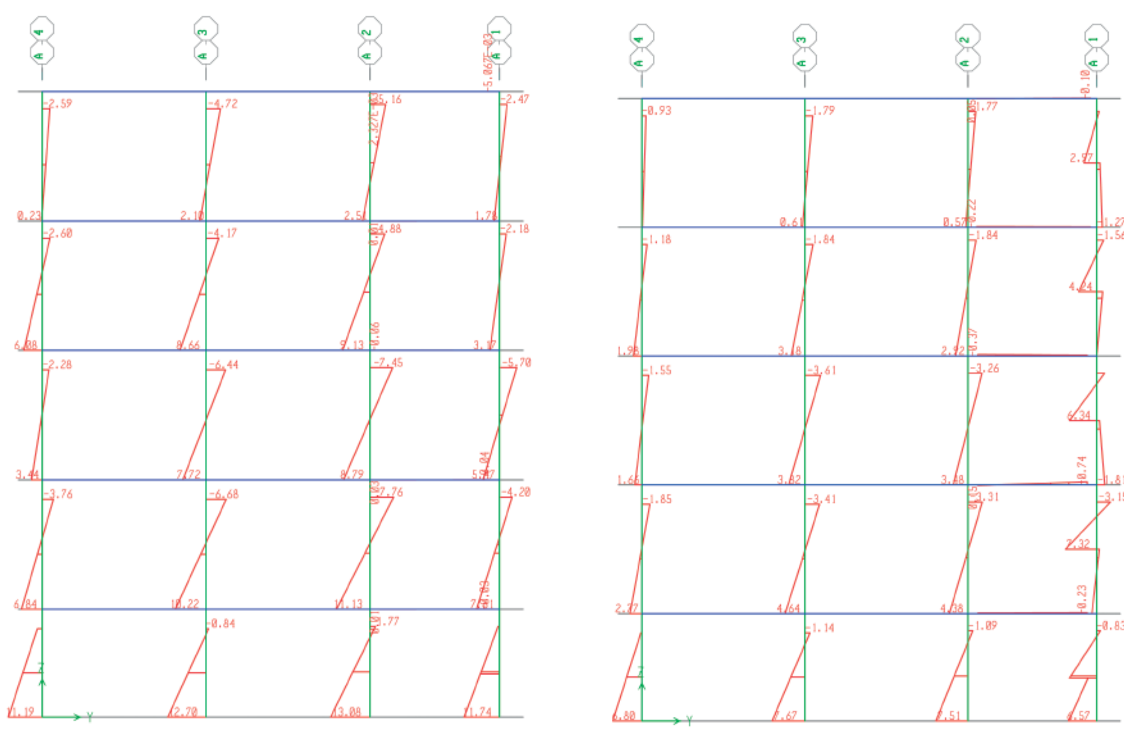

Figure 13.
Moment distribution under seismic force along Y direction (ton.m): (Left side) Model without stair case, (Right side) Model with staircase

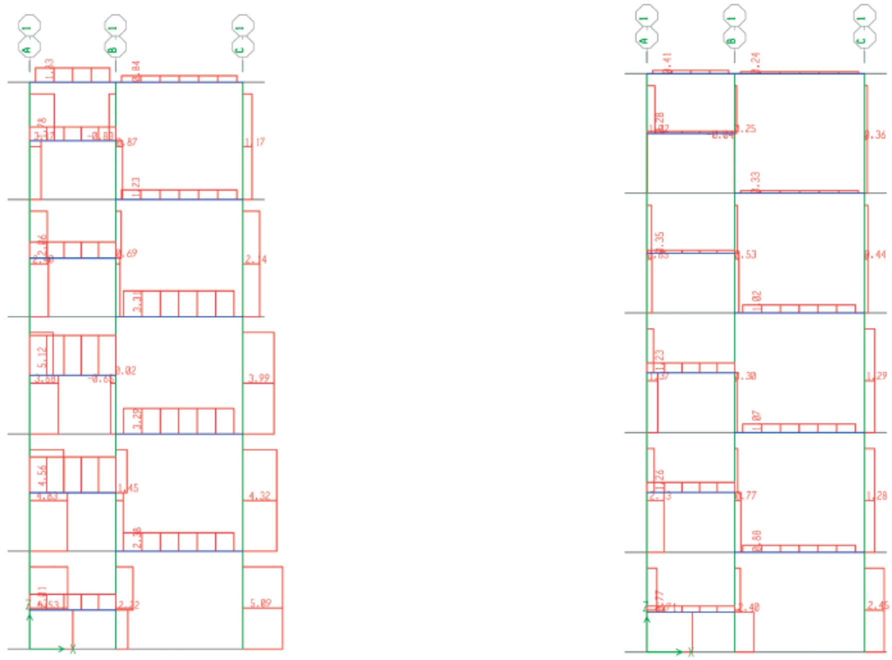

Figure 14.
Shear distribution under seismic force along X direction (ton): (Left side) Model without stair case, (Right side) Model with staircase

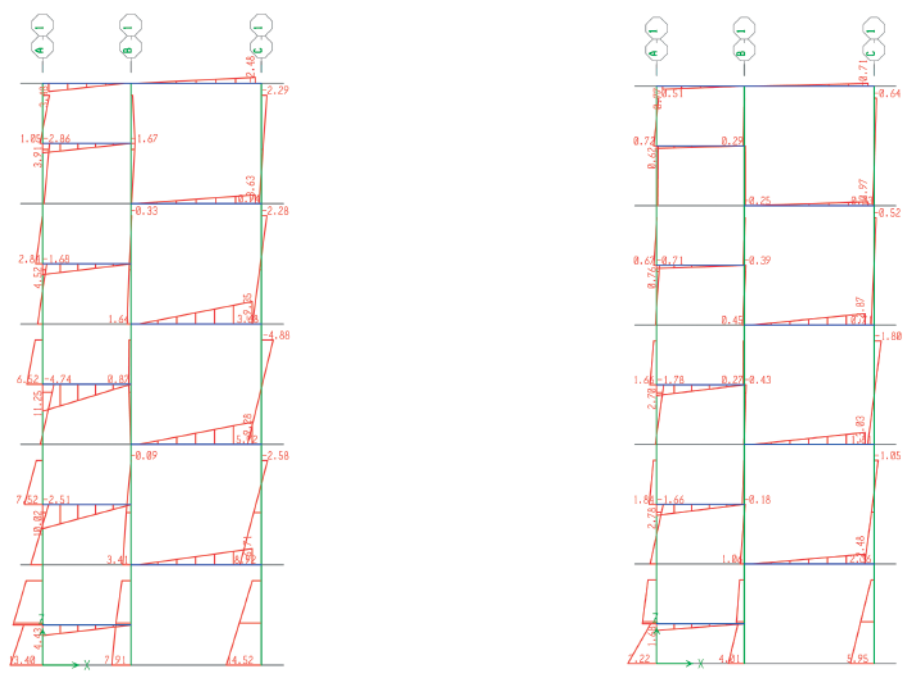

Figure 15.
Moment distribution under seismic force along X direction (ton.m): (Left side) Model without stair case, (Right side) Model with staircase

4. ENGINEERING SOLUTIONS

In reinforced concrete buildings, due to the adverse effects investigated above, even if the staircase is modeled, additional costs will be imposed on the structure and in some cases, due to a significant increase in shear forces, providing sufficient resistance is impossible. So, the best method to prevent adverse effects is to isolate staircase from master structure. This idea does not change the conventional structural design method, only special details in construction are necessary. An effective solution is to separate the stair with a sliding joint at each floor. Against lateral displacement, stairs slip on lower floors and therefore do not attract any lateral force (Fig. 16). Sliding joints which separate stair from master structure are formed easily. It is only necessary to prevent any possible connection between the stair and its base support [8, 4]. Some stairs are separated with more sophisticated materials such as Teflon strips sitting on stainless steel plates. This combination has very little friction. Separating the stair through roller at its base or more complex detail with a switch-back or dog-leg stair are possible solutions too [8]. In lightweight stairs, using slotted holes in connection of stair to floor is suitable for isolating.

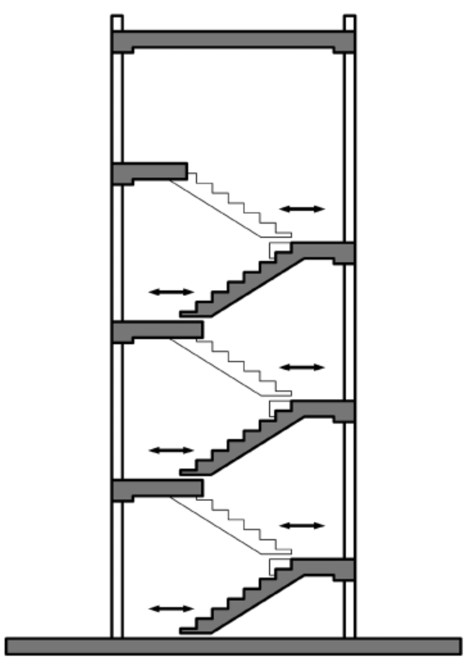

Figure 16.
Staircase isolated from master structure

5. CONCLUSION

The results of the analyses in five groups are presented as follows:

Group 1

The results of models in group 1 show that RC slab of staircase performs as a K-shaped bracing in longitudinal direction and as an inclined shear wall in transverse direction, so in both directions structural stiffness increases, period and lateral displacement of structure decrease, but staircase constructed by stringer beam only acts as a bracing in longitudinal direction and its effect in transverse direction can be neglected.

Group 2

By isolating the staircase from master structure, only location and dimension of staircase and arrangement of infill walls shall be studied. Based on the analyses of group 2, when the staircase is located at the corner, even the stair and infill walls are isolated from the structure, structural geometry is prone to torsion alone. Therefore, in this case the most appropriate geometry of the structure is to design stair, elevator and entrance space in one structural bay and use a uniform geometry in the entire structure. When the staircase is located at the middle of the length, structural geometry has no significant impact and all three structural geometries including uniform frames in the entire structure, shorter frame on the landing and shorter frames on both sides of staircase are acceptable. Although using uniform geometry in the structure has its advantages.

Group 3

Based on the results of group 3, to prevent torsional effects in one-bay structure with the staircase at the corner, hinge connections on the side of staircase or extra column on the opposite side of the staircase will be effective.

Group 4

The results of models in group 4 show that stiffness caused by small span, inclined RC slabs and perimeter infill walls of staircase, based on the location of staircase and the number of structural bays could change mode shape and lead to torsion due to changing the center of stiffness. Based on the geometry of plan and arrangements of infill walls, sometimes infills balance the concentration of stiffness caused by inclined slabs of staircase and sometimes intensify it.

Group 5

Based on the analyses of group 5, staircase changes force distribution fundamentally. In longitudinal direction shear force and bending moment of columns adjacent to landing beams increase enormously and short column occurs. Instead, forces of other members decrease. But in transverse direction, internal forces and moments in all structural elements reduce because an inclined slab of staircase performs as shear wall.

6. NOTATION LIST

Dir.: Direction of the dominant movement

EQX: Earthquake load in X direction

EQXP: Earthquake load in X direction with positive eccentricity

EQXN: Earthquake load in X direction with negative eccentricity

EQY: Earthquake load in Y direction

EQYP: Earthquake load in Y direction with positive eccentricity

EQYN: Earthquake load in Y direction with negative eccentricity

UX: Mass participation in X direction

UY: Mass participation in Y direction

%ex: Eccentricity along X direction

%ey: Eccentricity along Y direction

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