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Comparing calculation methods of storey stiffness to control provision of soft storey in seismic codes

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Abstract. Numerous buildings have been damaged or destroyed in previous earthquakes by developing soft storey. Almost all the seismic codes have provisions to prevent soft storey in structures, most of them have recommended the ratio of stiffness between adjacent storeys, but none of them has proposed the method to calculate the storey stiffness. On the other hand a great number of previous researches on stiffness have been focused on approximate methods and accurate methods by using analytical softwares have been almost neglected. In this study, six accurate methods for calculating the storey stiffness have been studied on 246 two-bay reinforced concrete frames. It is shown with the results of the statistical study and structural analysis that method 3 in which there is no modification of the original model and the forces with triangular distribution similar to seismic forces are applied to the center of mass of all storeys has acceptable accuracy and desirable efficiency for designing and controlling structures.

Keywords: storey stiffness; soft storey; calculation methods; earthquake; seismic codes

1. Introduction

One of the most important causes of damage to buildings in past earthquakes is soft storey. Soft storey occurs due to the discontinuity of stiffness in height. If the stiffness of a storey (usually ground storey) is significantly lower than that of the upper storeys, a significant portion of the lateral displacement concentrates on ground storey and soft storey is formed (Asteris 2003, Arnold 2006, Arslan and Korkmaz 2007, Mulgund and Kulkarni 2011, Tabeshpour et al. 2012, Harmankaya and Soyluk 2012, Caterino *et al*. 2013, Saiful *et al*. 2014, Varughese *et al*. 2015). Several factors can lead to the occurrence of this phenomenon; Sometimes the geometry and dimensions of the structural elements have not been properly designed for example greater height of columns, removing some columns, lateral bracings and shear walls in a story especially ground floor due to architectural design (Fig. 1) and sometimes reducing or eliminating infill walls in a storey leads to form soft storey (Özmen and Ünay 2007, Asteris 2003, Zhao *et al*. 2009, Arnold 2006, Mulgund and Kulkarni 2011, Yatağan 2011, Tabeshpour *et al*. 2012, Saiful *et al*. 2014,

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Fig. 1 Soft storey due to elimination of shear walls in ground floor of the Olive View medical center in the 1971 San Fernando earthquake (Arnold 2006)

Varughese *et al.* 2015).

Most of the seismic codes have provisions to prevent soft storey in structures, but none of them has proposed the method to calculate the storey stiffness. Tena-Colunga (2010) believes that stiffness is inherently dependent on the analytical tools. Some engineers obtain simpler equivalent shear models to control the irregularity provisions. On the other hand, some other engineers have preferred to use 3D models to calculate stiffness. The results of these two approaches are very different to evaluate the soft storey. Thus for the same building, shear model can identify soft storey based on seismic codes, but a flexural model would suggest that a soft storey condition could not be developed to the same code, so the building can be designed as a regular one (Tena-Colunga 2010). Schultz believes that storey stiffness is not affected much by the type of lateral load distribution (Schultz 1992). As expected, comparison of different methods shows that the results lead to a good approximation when the structure is close to shear model, but the results are different when the structure is close to flexural model (Caterino *et al.* 2013).

Most of the research on stiffness has been focused on approximate methods and accurate methods have been studied less. In this study to answer three following questions, first, approximate calculation methods of stiffness are reviewed briefly. Then effective factors on evaluation of soft storey and provisions of many seismic codes are studied. In the next section accurate methods which are used in literature and professional society of civil engineers for calculating stiffness are investigated. In the main part of this paper, all of the accurate calculation methods of stiffness are used on two-bay reinforced concrete frames. Finally, the most efficient method which has acceptable accuracy and is useful for structural designers is selected by statistical and structural analysis.

1. Which methods are used to calculate the storey stiffness?
2. Which calculation method of storey stiffness is closer to reality?
3. Which calculation method of storey stiffness is more accurate and much easier for structural designer?

It is also important to note that when a general finite element building model is simplified to a shear building in which each spring is storey stiffness and each mass is storey mass, stiffness matrix of the generated system is three diagonal. Now there is an essential question: Is such a three diagonal stiffness matrix unique? If not, why and how? This paper is discussing about this question. There are important problems call “vibration inverse problems” based on three diagonal stiffness matrix. Such problems are in the field of finite element updating and system identification (Tabeshpour 2012). The results of this paper can be directly used in these types of problems.

2. Approximate calculation methods of storey stiffness

In literature, there are several methods to calculate approximate storey stiffness manually, but accurate methods by using analytical softwares are almost neglected. It is necessary to note that the most of approximate methods are based on the methods proposed by Wilbur *et al*. Some of these include three approximate methods for analyzing building frames against lateral loads; the portal method, the cantilever method, the factor method and a fundamental assumption about the inflection point of columns and girders which is located at the mid-points (Wilbur *et al*. 1975). In this section approximate methods are studied to extract principles for analyzing accurate methods. According to the main purpose of this review, details and proposed formula of these methods are not presented. In the method proposed by Heidebrecht and Stafford Smith in 1973, the sub-frame includes two half-height columns at the top and bottom of considered storey and two beams. The inflection points are assumed at mid-height of columns and mid-span of beams, so the sub-frame is separated by the 4 points of zero bending moment from the main frame (Heidebrecht and Stafford Smith 1973). In the proposed method of Schultz in 1992, one storey includes all columns as well as a portion of top and bottom beams are isolated from the rest of the frame. In this method, only the inflection points of columns in intermediate storeys of uniform frames with many storeys are assumed close to the mid-height. For simulating the effect of variation in adjacent storey height, boundary storeys (first, second and top), and the effect of a fixed base in low-rise buildings, the correction factors have been proposed (Schultz 1992). In the method proposed by Paulay and Priestley in 1992, the sub-frame includes a full-height column and half-length of four beams adjacent. The inflection points of beams are assumed at mid-span (Paulay and Priestley 1992). Hosseini and Imagh-e-Naiini proposed a quick method for estimating the stiffness of regular and irregular moment frame, braced frames and frames with shear walls in 1999. In this method, the main frame is substituted with equivalent frames which are connected to each other by hinges. The basic ideas, in this method are based on these facts that in moment frame, all of the beams and columns deformed similarly, the lateral stiffness of each floor is mainly due to columns and beams just below and above that floor, and in lateral stiffness of a braced frame, the effect of axial deformations of beams and columns on their flexural behaviour are neglected (Hosseini and Imagh-e-Naiini 1999). In 2000, Ramasco proposed a method in which the planar frame modeled as an equivalent cantilever. At each level of this cantilever, the second moment of area is equal to the sum of the moments of inertia of the columns in that level. The rotational restraint offered by the beams is modeled applying rotational springs to cantilever at the corresponding level. It is assumed that bending moment is zero at mid-height of columns, and for the first floor at two-thirds of the height from bottom (Ramasco 2000). Caterino *et al*. proposed a method in 2013. In this method, a sub-frame includes the full-height column, beams and columns above and below the level under examination which are separated from the remaining structure at points of zero bending moment, so there is only shear force at these points. First, points of zero bending moment of columns above and below should be calculated, but similarly to existing methods, these points are assumed to be located at mid-span of beams. For the first storey, it is assumed that column is fully restrained against rotation at the base, so the model has a full-height column, two beams and a part of column at its top. The model of last storey is similar to the others, but it is only needed to consider an auxiliary column that ideally extends the real one above the roof (Caterino *et al*. 2013).

3. Effective parameters on evaluation of soft storey

Structural system, stiffness and mass distribution and stiffness calculation methods can be considered as four effective parameters on evaluation of soft storey (Fig. 2). All of these parameters have been investigated as follow, but it should be noted the main scope of this study and analytical models are concentrated on stiffness calculation methods.

3.1 Effect of shear model and flexural model on evaluation of soft storey

Based on behaviour of structures against lateral forces, two different systems can be defined; flexural model and shear model, but it should be indicated that these are extreme cases, where between them infinite real cases may exist. In flexural system, structural elements bear axial forces. Shear walls and braced frames are classified in this group. In shear model, structural elements bear bending moment. Structures such as moment frames are classified in this group. Seismic force distribution and lateral displacement of these two systems are different. According to the seismic force distribution, there is a slight increase in storey shear of shear wall and braced frame from upper floors to lower floors, so drift of lower floors will not be much more than upper ones. In moment frame, based on seismic force distribution, storey shear of lower floors is much more than upper ones, so drift of these floors will be more than upper ones too. Therefore, the potential of soft story in moment frame is greater than shear walls or braced frames (Fig. 3).

On the other hand, based on beam to column stiffness, two different models can be defined. In shear model beam is much stiffer than column, on the contrary, in flexural model column is much stiffer than beam. Lateral displacement shape and moment distribution along the height of building are very different in these two models (Fig. 4). In shear model, the inflection points occur at mid-height of the elements, but in flexural models that have a combined flexural and shear behaviour,

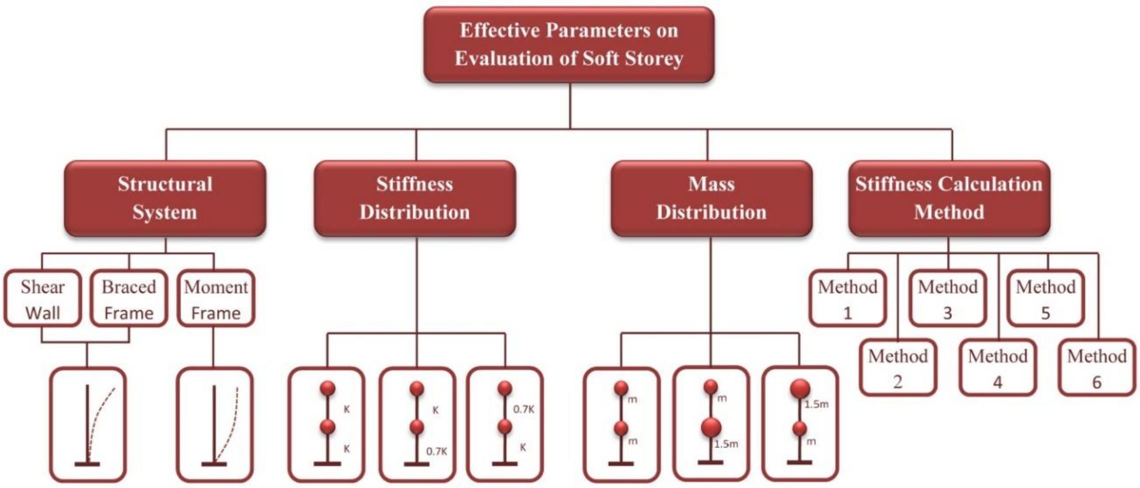


Fig. 2 Effective parameters on evaluation of soft storey

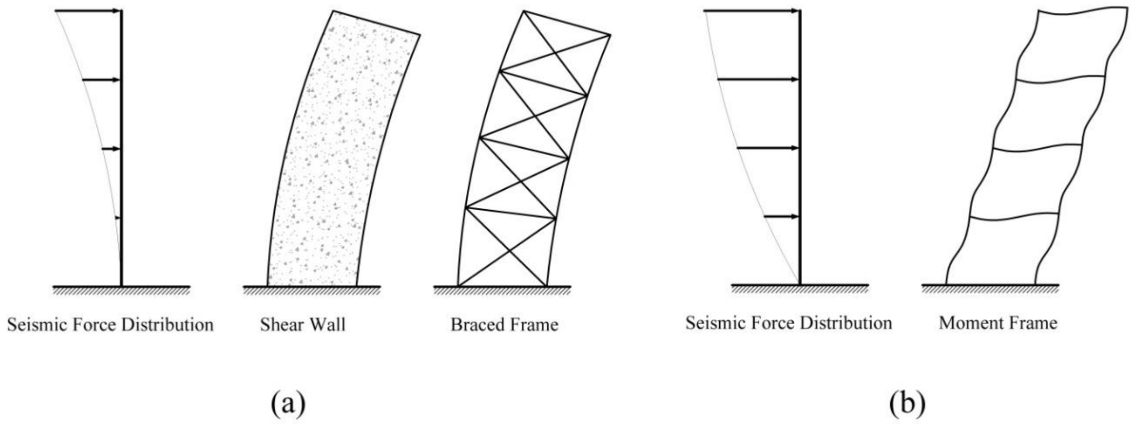


Fig. 3 Seismic force distribution and lateral displacement of structures; (a) Shear wall and braced frame, (b) Moment frame

the inflection point of columns may not necessarily be located at the mid-height and in some cases, specially first storey, they may be out of the height of the column (Caterino *et al*. 2013). Shear buildings owe their popularity to the simplicity of equilibrium equations and ease of calculation. In this model, all mass at a storey is placed at the corresponding lateral degrees of freedom. Joint rotations are assumed to be equal to zero and beams are rigid in relation to columns. The lateral stiffness of a storey is obtained by combining all columns stiffness into a single elastic spring that connects the lateral degrees of freedom to adjacent storeys. Shear buildings are usually used to study the response of moment frames against lateral forces (Schultz 1992). The behaviour of flexural models is similar to flexural vertical cantilever beams connected by axially rigid members at each level (Caterino *et al.* 2013) (Fig. 5). Despite the fact that the shear models can be used for both braced frames and moment frames, but as usual shear models are suitable to study moment frames, flexural models are suitable to study braced frames or shear walls. Calculated stiffness by shear models are usually greater than flexural models, because in shear models, the reduction caused by columns and beams end rotation is neglected. In addition, beams are usually assumed to be axially rigid in shear model. These extra constraints make shear models stiffer than flexural models. By using shear models, greater differences are usually calculated between the lateral stiffness of adjacent storeys in comparison with flexural ones (Tena-Colunga 2010). Most of calculation methods of stiffness are based on the assumption that the structure behaviour is similar to shear model, so these methods do not always lead to desirable results for new buildings which are designed based on the capacity design philosophy that derives from strong column-weak beam systems (Caterino *et al.* 2013).

3.2 Effect of stiffness distribution on soft storey based on seismic codes

The soft storey condition is recognized as vertical irregularity in seismic codes since 1987, the first seismic code includes the recommendation is the Mexico's federal district code (Tena-Colunga 1999). To prevent soft story according to ASCE 7-10, NZS 1170.5 (New Zealand Standard), IS 1893 (Indian Standard) and standard No.2800 (Iranian standard) as a condition of

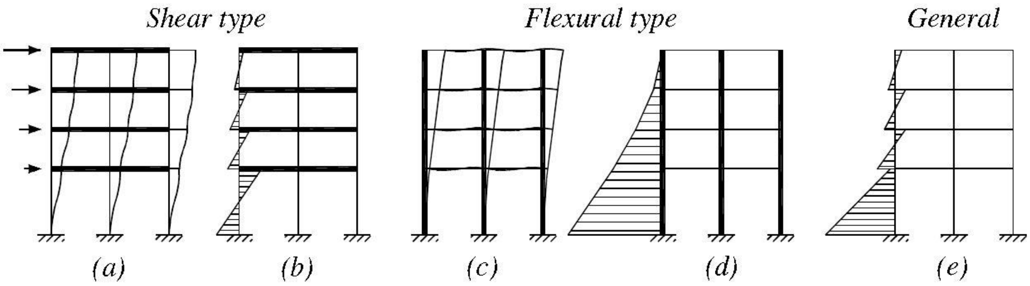


Fig. 4 Lateral displacement shape and moment distribution in shear and flexural models; (a) Lateral displacement of shear model, (b) Moment distribution of shear model, (c) Lateral displacement of flexural model, (d) Moment distribution of flexural model, (e) Moment distribution of flexural-shear model (Caterino *et al.* 2013)

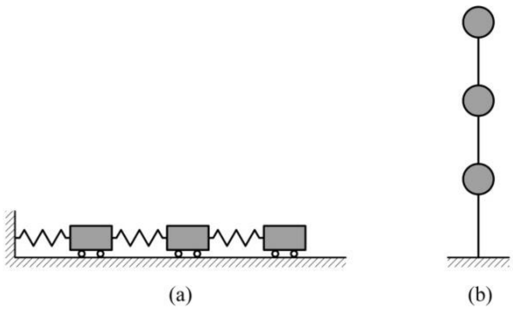


Fig. 5 Equivalent models for calculating storey stiffness; (a) Shear model, (b) Flexural model

vertical regularity, the lateral stiffness of each storey shall not be less than 70% of that in the storey above or 80% of the average stiffness of the three storeys above (ASCE 7-10 2010, NZS 1170.5.2004 2004, IS 1893 2002, Standard No. 2800 2015). There is the same provision in Australian standard 1170.4-1993, but it is omitted in new version of 2007 (AS 1170.4-1993 1993, AS 1170.4-2007 2007) Eq. (1). In RCDF-04 and NTCS-04 (the current Mexican seismic code) this ratio is 67% (RCDF-04 2004; NTCS-04 2004)

$$k_i < 0.7k_{i+1} \quad or \quad k_i < 0.8\left(\frac{k_{i+1}+k_{i+2}+k_{i+3}}{3}\right) \tag{1}$$

In seismic code of Turkey as a condition of inter storey stiffness irregularity (soft storey) has been indicated that Stiffness Irregularity Factor which is defined as the ratio of the average relative storey drift at any storey to the average relative storey drift at the storey immediately above or below, is greater than 2 in each of the two orthogonal directions, ±%5 additional eccentricities shall be considered in calculation (Specification for Structures to be Built in Earthquake Areas 2007) Eq. (2)

$$\eta_{ki} = \frac{\left(\Delta_i/h_i\right)_{avr}}{\left(\Delta_{i+1}/h_{i+1}\right)_{avr}} > 2 \quad \text{or} \quad \eta_{ki} = \frac{\left(\Delta_i/h_i\right)_{avr}}{\left(\Delta_{i-1}/h_{i-1}\right)_{avr}} > 2 \tag{2}$$

Table 1 Converting the provision of soft storey in seismic code of Turkey into the other countries

Number of storeys	Stiffness of first to second storey	Stiffness of penultimate to last storey
2	75%	-
3	60%	83%
4	55%	87%
5	53%	90%
10	50%	95%

Table 2 Summarized provisions of soft storey in seven seismic codes

	ASCE 7-10	NZS 1170.5 of New Zealand	Australian standard 1170.4-1993	IS 1893 of India	Standard No. 2800 of Iran	RCDF-04 NTCS-04	Seismic code of Turkey
The ratio of lateral stiffness of each story to the story above or the average of the three storeys above	70% 80%	70% 80%	70% 80%	70% 80%	70% 80%	67%	-
The ratio of the average relative story drift at any story to the story immediately above or below	-	-	-	-	-	-	2

According to the above, provision of Turkey will compare with other countries in the following. Since the distribution of seismic forces at the height of the building is triangular, so for the first floor of a three-storey building, the provision of soft storey in seismic code of Turkey will be converted into the other countries by Eq. (3)

$$\frac{\Delta_1}{\Delta_2} = \frac{6F/_{K_1}}{5F/_{K_2}} = \frac{6K_2}{5K_1} > 2 \longrightarrow \frac{K_1}{K_2} < 0.6 \tag{3}$$

The results of similar calculations as the stiffness of first to second storey and penultimate to last storey are summarized in Table 1. The results show that the proposed provision of Turkey is different from other countries and depending on the number of storeys and considered storey, different equation will be obtained. The provision of soft storey of seven countries is summarized in Table 2.

3.3 Effect of mass distribution on soft storey

In ASCE 7-10, NZS 1170.5 (New Zealand Standard) and standard No.2800 (Iranian standard) as a condition of vertical regularity is mentioned that the effective mass of any storey shall not be more than 150% of the effective mass of an adjacent storey (ASCE 7-10 2010, NZS 1170.5.2004 2004, Standard No. 2800 2015). There is the same provision in Australian standard 1170.4-1993, but it is omitted in new version of 2007 (AS 1170.4-1993 1993, AS 1170.4-2007 2007). This ratio is 200% in IS 1893 (Indian Standard) (IS 1893, 2002) and in this regard, there is nothing in seismic code of Turkey (Specification for Structures to be Built in Earthquake Areas 2007). In RCDF-04 and NTCS-04 (the current Mexican seismic code) the weight of any storey shall not be less than 70% and more than 110% the weight of adjacent storey below the one in consideration (RCDF-04 2004; NTCS-04 2004). The provision of mass irregularity of seven countries is summarized in Table 3.

In Fig. 6 three cases of mass distribution of a structure with stiffness irregularity are presented. In the first case, mass distribution is regular and all of the storeys have the same mass. Two other cases have mass irregularity in height, in second case, mass of top storey is greater and in third case, mass of bottom storey is greater. Since total height and mass of the structure are similar in all three cases, lateral seismic force will be the same, but its distribution in elevation is different. Storey shear is proportional to the storey mass and height of the storey from the foundation. Considering the lateral seismic force distribution show that seismic force of second storey in third case is less than others and as a result drift difference between second and first storey is more. This means that the soft story failure risk in third case is higher. As the storey shear and storey stiffness are determined, storey drift can be calculated. The storey drift and the ratio of first to second storey drift are presented in Table 4. It is shown that based on seismic code of Turkey in third case, soft storey will be more severe than others. Accordingly, it should be mentioned that it is necessary to study stiffness distribution and mass distribution of adjacent storeys simultaneously to control soft storey because sometimes mass distribution will intensify soft storey in building with stiffness irregularity and sometimes mass distribution will cause soft storey occurs in buildings which are on the verge of stiffness irregularity.

Table 3 Summarized provisions of mass irregularity in seven seismic codes

	ASCE 7-10	**NZS 1170.5 of New Zealand**	**Australian standard 1170.4-1993**	**IS 1893 of India**	**Standard No. 2800 of Iran**	**RCDF-04 NTCS-04**	**Seismic code of Turkey**
The ratio of effective mass of any storey to the adjacent storey	150%	150%	150%	200%	150%	$0.7 \leq \frac{W_i}{W_{i-1}} \leq 1.1$	-

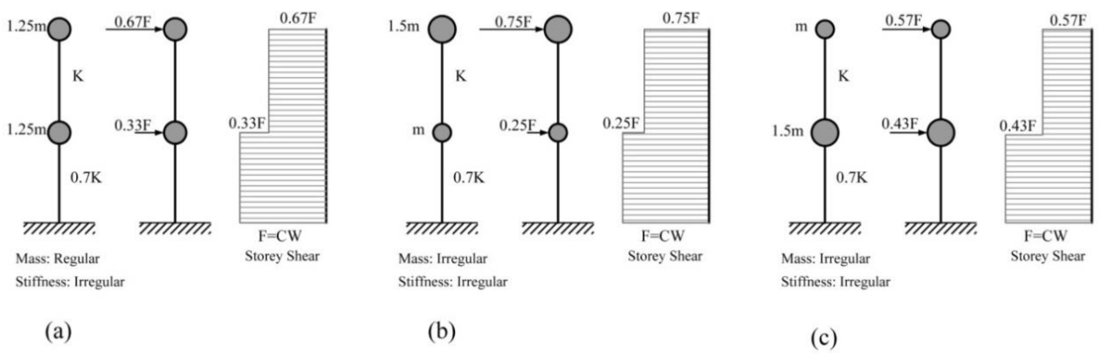


Fig. 6 Effect of mass distribution on intensification of soft storey in buildings with stiffness irregularity; (a) Regular mass distribution, (b) Irregular mass distribution, more mass on top storey, (c) Irregular mass distribution, more mass on bottom storey

Table 4 Storey drift of Fig. 6 cases and the ratio of first to second story drift

Case	Δ_1	Δ_2	Δ_1/Δ_2
Case (a)	$1.43\frac{F}{K}$	$0.67\frac{F}{K}$	2.13
Case (b)	$1.43\frac{F}{K}$	$0.75\frac{F}{K}$	1.90
Case (c)	$1.43\frac{F}{K}$	$0.57\frac{F}{K}$	2.50

3.4 Accurate calculation methods of storey stiffness

In this section, six accurate calculation methods of storey stiffness by using software include four common methods in professional society of civil engineers and two proposed ones are presented (Fig. 7):

Method 1: In this method, there is no modification in original model, the force is applied to the center of mass of last storey and by calculating the drift of any storey, the stiffness of that storey is obtained.

Method 2 (Proposed): In this method, there is no modification in original model, the force is applied to the center of rigidity of each storey individually and by calculating the drift of that storey, the storey stiffness is obtained.

Method 3: In this method, there is no modification in original model, the forces with triangular distribution similar to seismic force distribution is applied to the center of mass of all storeys and by calculating the drift of any storey, the stiffness of that storey is obtained.

Method 4: This method is based on the finite element method. In this method, pinned supports are added to upper and lower storey of considered one to eliminate the horizontal displacement and the force is applied to the center of rigidity of considered storey. By calculating the drift of the storey, the total stiffness of two adjacent storeys is calculated. Since the stiffness of last storey is just for one storey, by subtracting the stiffness of upper storey respectively, the stiffness of each storey will be obtained.

Method 5 (Proposed): In this method, there is no modification in original model, the force is applied to the center of rigidity of considered storey and the equal force in the opposite direction is applied to the center of rigidity of lower storey. By calculating the drift of considered storey, the storey stiffness will be obtained.

Method 6: In this method, all of the storeys which are located above the considered storey are deleted and the bottom of columns is constrained. By applying the force to the center of rigidity of considered storey, storey stiffness will be calculated.

4. Analytical models

In order to do quantitative analysis and compare these methods, two-bay reinforced concrete frames are modeled in structural analysis software. Their material specifications and sections of members are presented in Tables 5, 6. To reduce the variables, in each frame the section of members in all of storeys are the same. To study the effective factors on the storey stiffness, 24 types of frame which are obtained by multiplying the following variables are considered for six above methods (Fig. 8), so 246 frames are modeled and the results are analyzed.

Number of Storeys (two types): includes two and three-storey, to study the stiffness ratio of second storey to first storey in different methods.

Moment of Inertia of Beam Section (three types): includes the beam width equal to one-half, one and twice the column width, to study the effect of beam stiffness on storey stiffness in different methods and to study the effect of the strong column-weak beam principle.

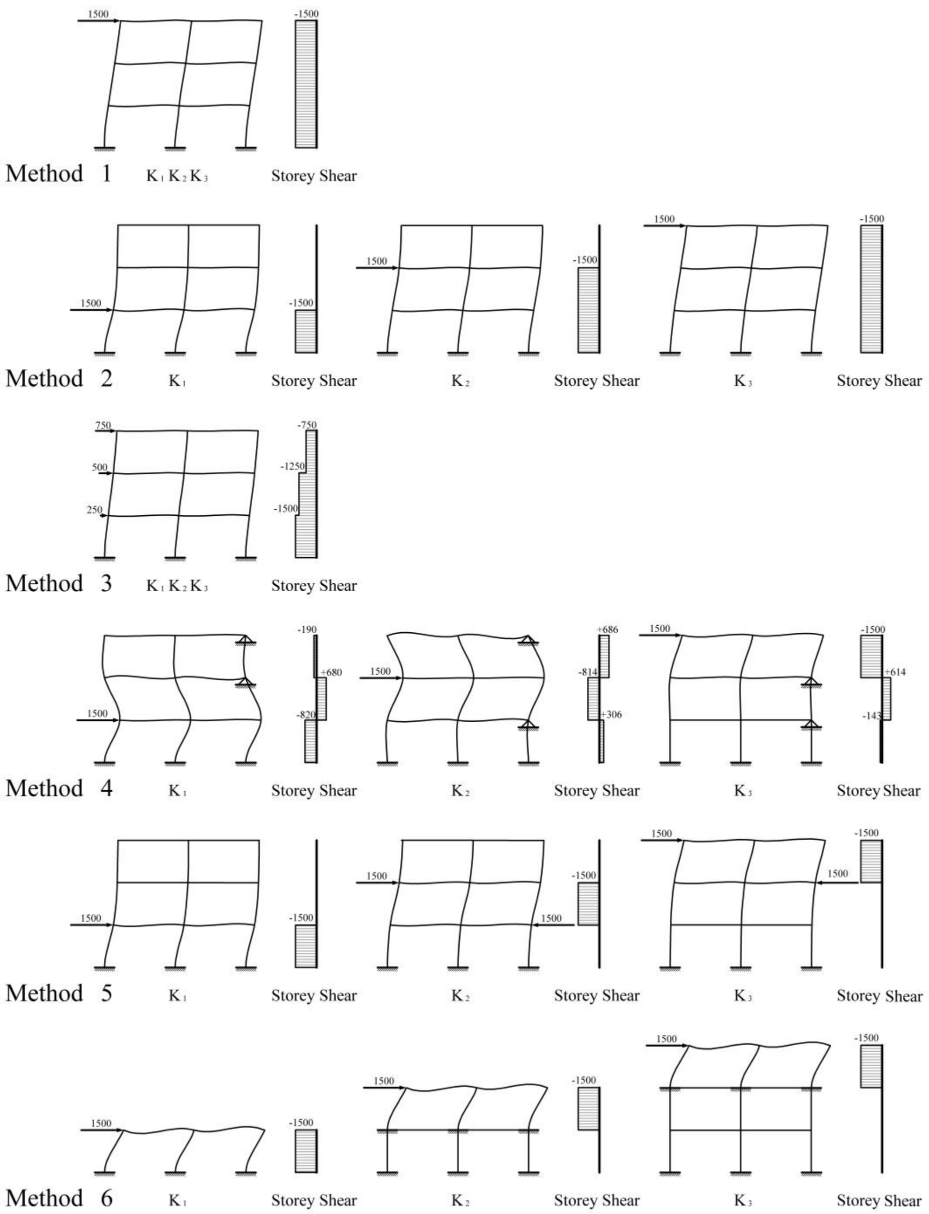


Fig. 7 Six accurate calculation methods of Storey Stiffness

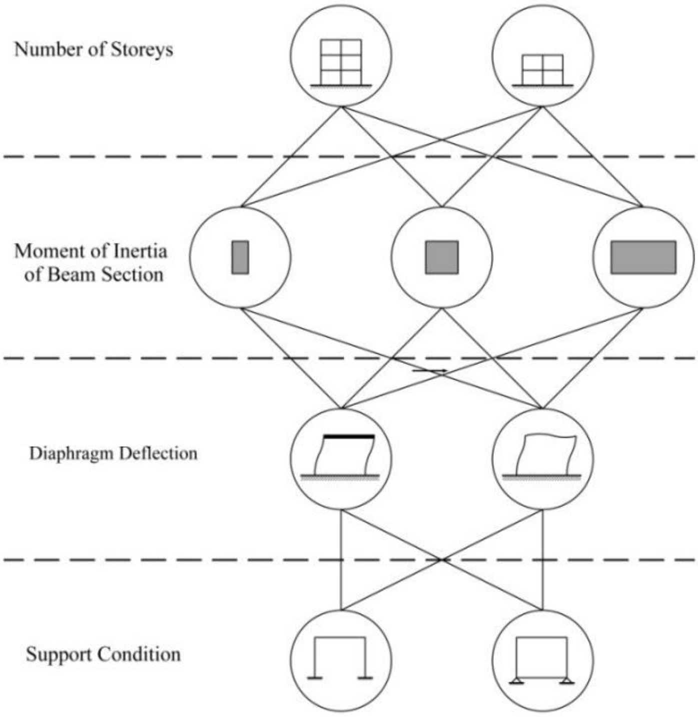


Fig. 8 Four variables and 24 types of frame to study calculation methods of Storey Stiffness

Table 5 Concrete and rebar properties

Density	**Modulus of Elasticity**	**Poisson's Ratio**	**f'c Concrete compressive Strength**	**fy Bending Reinforcement Yield Stress**	**fys Shear Reinforcement Yield Stress**
kN/m^3	N/mm^2		N/mm^2	N/mm^2	N/mm^2
25	24516	0.15	24.5	392	392

Table 6 Section of members

Name	**Type**	**Dimension** cm
C	Column	40, 40
0.5B	Beam	20, 40
B	Beam	40, 40
2B	Beam	80, 40

Diaphragm Deflection (two types): includes diaphragm with out-of-plane deflection and without out-of-plane deflection. For the first type, Young's modulus of beam is assumed equal to column and for the second type, ten times the column, to compare flexural and shear model in different methods.

Support Condition (two types): includes rigid and pinned with a link beam at foundation, in second type, the support condition of first storey becomes similar to the other storeys, so the storey stiffness can be compared with each other in different methods because of same section of members in all storeys.

5. Results

In this section, results of calculation for each of the methods in 24 types of the frame are presented in the form of charts. In Fig. 9, results of storey stiffness of three-storey frames for two conditions of Young's modulus of beams equal to columns and ten times of column in two types of rigid and pinned supports for different width of beam is presented. In Fig. 10 the same results for two-storey frames are presented. Because of the large amount of calculations, only the results of the three-story frame with width and Young's modulus of beams equal to columns and rigid supports are presented in Table 7. Additional charts have been extracted to analyze the results based on the selected variables (Fig. 11 to 13). In Fig. 11, stiffness of three-storey frames with width and Young's modulus of beams equal to columns in two types of rigid and pinned supports and in Fig. 12, stiffness of three-storey frames with width of beams equal to columns and rigid supports in two types of Young's modulus of beams equal to columns and ten times the columns are compared. In Fig. 13, comparison between the stiffness of first and second storey in three-storey and two-storey frames with width and Young's modulus of beams equal to columns and rigid supports are presented.

Table 7 The results of calculating the storey stiffness for three-story frame with beams width equal to columns width and rigid supports by using six methods

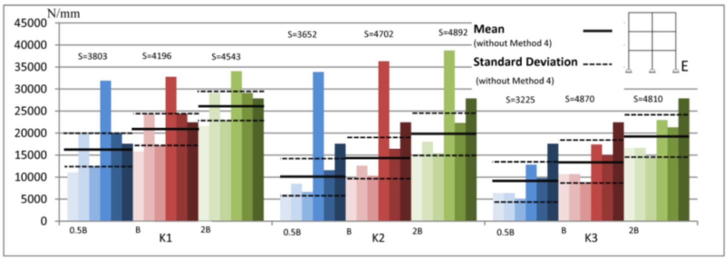
				Method 1				
mm, N/mm	**First Storey**			**Second Storey**			**Third Storey**	
	Δx	**Kx1**	**Kx1/ Kx2**	**Δx**	**Kx2**	**Kx2/ Kx3**	**Δx**	**Kx3**
E	0.949	15806	1.62	1.538	9753	0.91	1.403	10691
10E	0.439	34169	1.17	0.515	29126	0.94	0.482	31120
				Method 2				
mm, N/mm	**First Storey**			**Second Storey**			**Third Storey**	
	Δx	**Kx1**	**Kx1/ Kx2**	**Δx**	**Kx2**	**Kx2/ Kx3**	**Δx**	**Kx3**
E	0.615	24390	1.93	1.19	12605	1.18	1.403	10691
10E	0.397	37783	1.19	0.473	31712	1.02	0.482	31120
				Method 3				
mm, N/mm	**First Storey**			**Second Storey**			**Third Storey**	
	Δx	**Kx1**	**Kx1/ Kx2**	**Δx**	**Kx2**	**Kx2/ Kx3**	**Δx**	**Kx3**
E	0.874	17162	1.67	1.213	10305	1.16	0.845	8876
10E	0.431	34803	1.17	0.422	29621	1.01	0.256	29297

Table 7 Continued

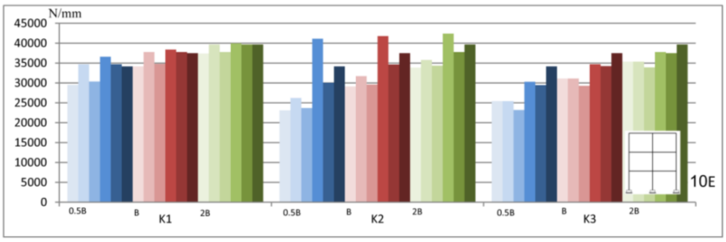
Method 4										
mm, N/mm	First Storey				Second Storey				Third Storey	
	Δx	Kx1+Kx2	Kx1	Kx1/ Kx2	Δx	Kx2+Kx3	Kx2	Kx2/ Kx3	Δx	Kx3
E	0.217	69124	32803	0.90	0.279	53763	36322	2.08	0.86	17442
10E	0.187	80214	38406	0.92	0.196	76531	41808	1.20	0.432	34722

Method 5								
mm, N/mm	First Storey			Second Storey			Third Storey	
	Δx	Kx1	Kx1/ Kx2	Δx	Kx2	Kx2/ Kx3	Δx	Kx3
E	0.615	24390	1.48	0.913	16429	1.09	0.999	15015
10E	0.397	37783	1.09	0.433	34642	1.01	0.438	34247

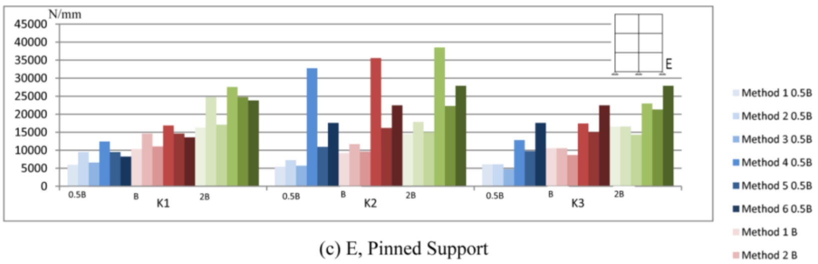
Method 6								
mm, N/mm	First Storey			Second Storey			Third Storey	
	Δx	Kx1	Kx1/ Kx2	Δx	Kx2	Kx2/ Kx3	Δx	Kx3
E	0.668	22455	1.00	0.668	22455	1.00	0.668	22455
10E	0.4	37500	1.00	0.4	37500	1.00	0.4	37500



(a)E, Rigid Support

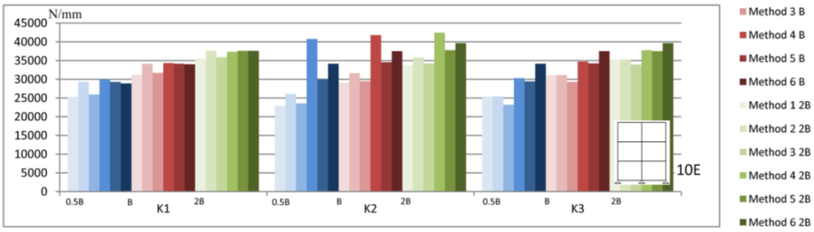


(b)10 E, Rigid Support



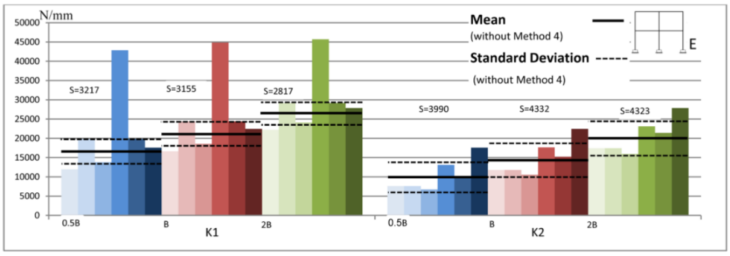
(c) E, Pinned Support

Fig. 9 Stiffness of three-storey frames

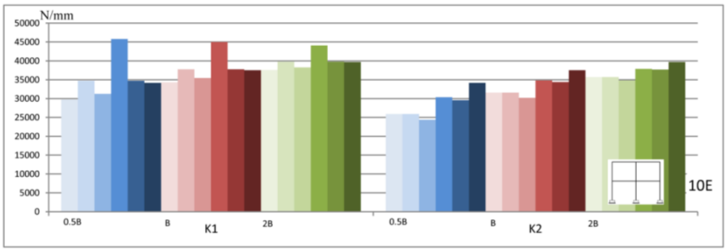


(d) 10E, Pinned Support

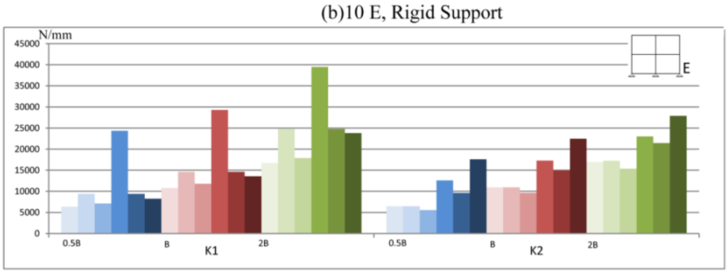
Fig. 9 Continued



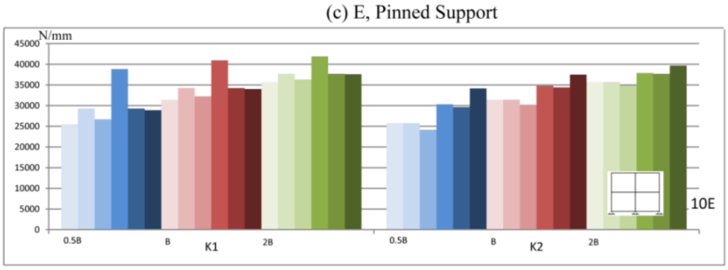
(a)E, Rigid Support



(b)10 E, Rigid Support



(c) E, Pinned Support



(d) 10E, Pinned Support

Fig. 10 Stiffness of two-storey frames

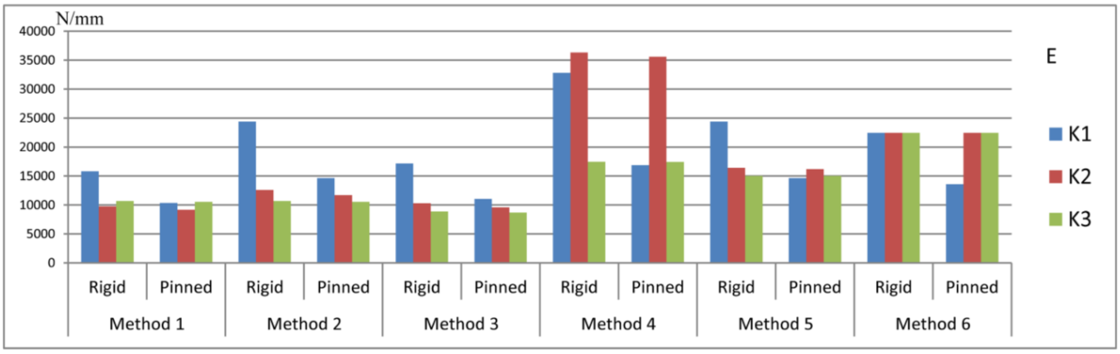


Fig. 11 Stiffness of three-storey frames with width and Young's modulus of beams equal to columns in two types of rigid and pinned supports

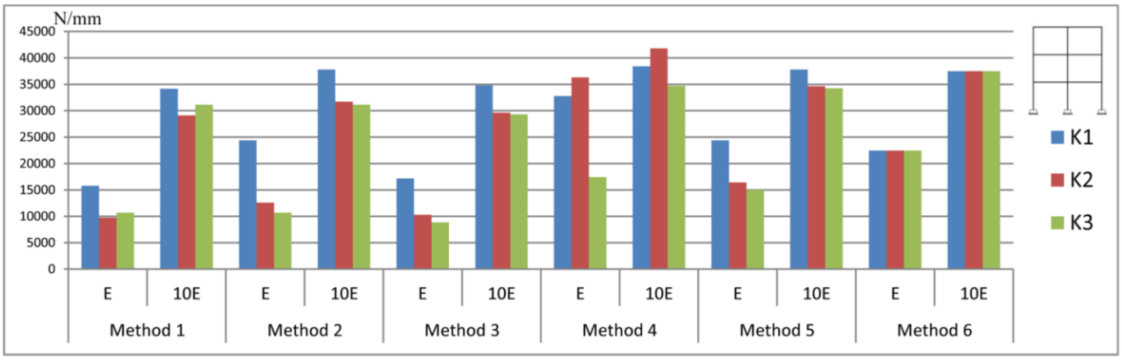


Fig. 12 Stiffness of three-storey frames with width of beams equal to columns and rigid supports in two types of Young's modulus of beams equal to columns and ten times the columns

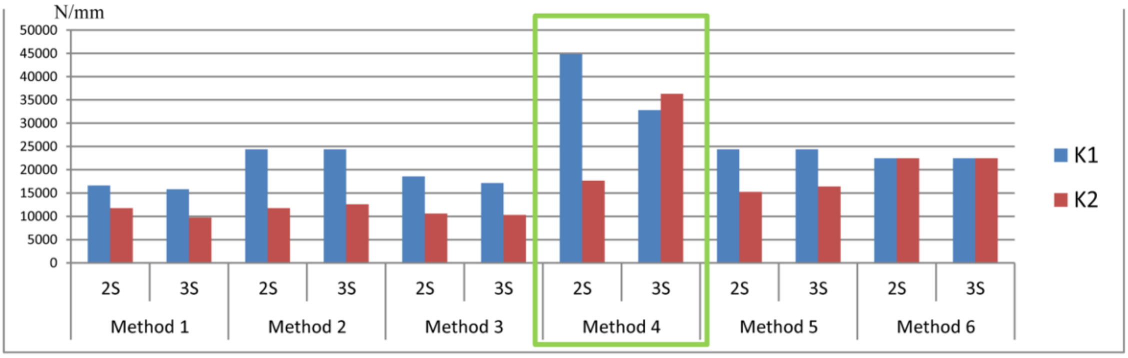


Fig. 13 Comparison between the stiffness of first and second storey in three-storey and two-storey frames with width and Young's modulus of beams equal to columns and rigid supports

6. Discussion

In this section, the results are investigated by using three approaches include descriptive study, statistical study and structural analysis. Descriptive studies are presented in two sections based on methods and based on variables.

6.1 Descriptive study

6.1.1 Descriptive study based on methods

Method 1

• Except the last storey, minimum storey stiffness is obtained by using this method

• The stiffness of last storey is similar to method 2 (obvious).

Method 2

• The stiffness of last storey is similar to method 1 (obvious).

• The stiffness of first storey is similar to method 5 (obvious).

Method 3

• The calculated stiffness by using this method is almost similar to method 1, except the last storey which is less.

Method 4

• Except the last storey, in this method the storey stiffness is much more than the others.

Method 5

• The stiffness of first storey is similar to method 2 (obvious).

Method 6

• In this method, the stiffness of all storeys is the same (obvious).

• In three-storey frames, by using this method after method 4, the stiffness of second storey (middle one) is obtained more than other methods.

• In this method, the stiffness of last storey is more than the other methods.

• In frames with pinned supports, the stiffness of first storey is less than upper storeys (obvious).

6.1.2 Descriptive study based on variables

Number of Storeys

• Except method 4, in other methods, the stiffness of first and second storey in two-storey frames is almost as same as three-storey frames (The stiffness in three-storey frames is slightly less than two-storey frames) (Fig. 13).

• By using method 4 like other methods, in two-storey frames, the stiffness of first storey is obtained greater than second storey, but in three-storey frames, the stiffness of second storey is obtained greater than first storey, this is not observed in any other methods (Fig. 13).

Moment of Inertia of Beam Section

• In all methods, increase of beams' moment of inertia leads increase of storey stiffness. Slope of these changes is almost the same in all methods (Figs. 9,10) but, in method 4, this slope is less than other methods, even in two-storey frames with rigid supports and Young's modulus of beams ten times the columns, the slope of first storey stiffness is negative (Fig. 10(b)).

Diaphragm Deflection

• By increasing Young's modulus of beams to ten times the columns, in order to protect out-of-plane deflection of diaphragms, the difference between the methods is reduced. By using method 4 or 6, depending on the storey the maximum stiffness is calculated.

• In all methods, increase of Young's modulus of beams leads increase of storey stiffness (obvious).

• Except method 4, by increasing Young’s modulus of beams, the difference between the stiffness of first and second storey is reduced. In method 4, the difference between the stiffness of second and third storey is reduced (Fig. 12).

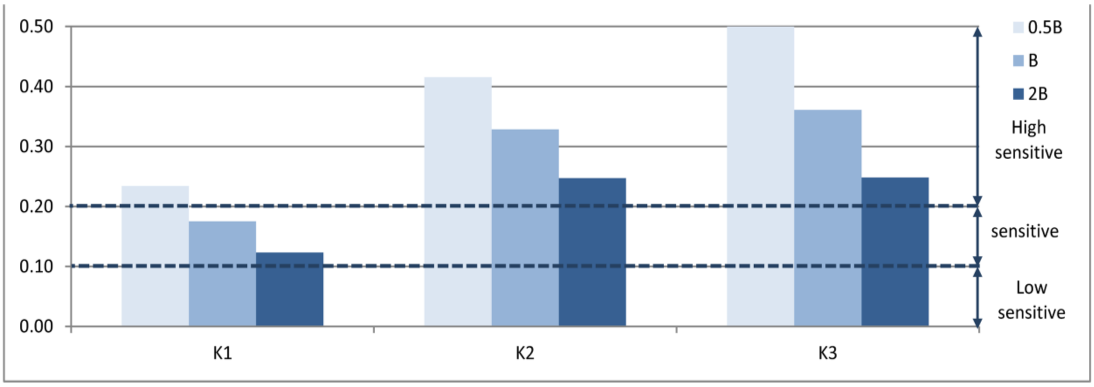
Support Condition

• Pinned supports only reduce the stiffness of first storey in all methods and do not have any significant effects on the stiffness of other storeys (Fig. 11).

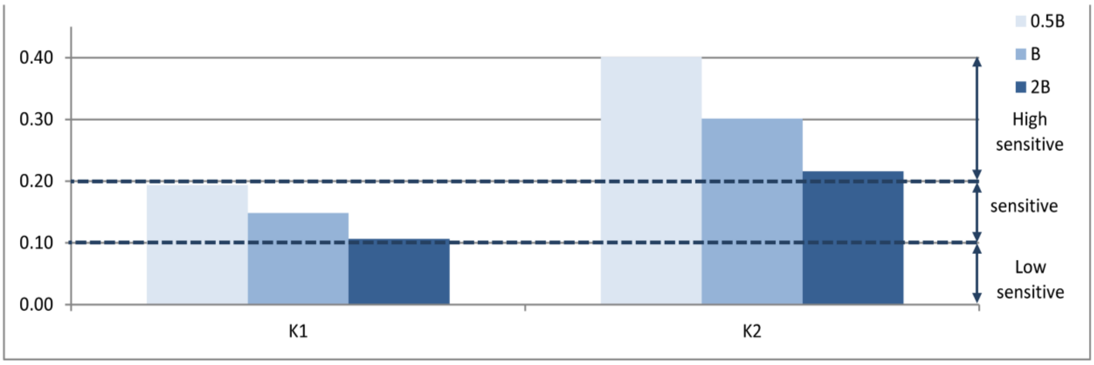
6.2 Statistical study

Statistical indicators have been calculated only for real models in which width and Young’s modulus of beams are equal to columns and the supports are rigid. Method 4 has been omitted from calculations of mean and standard deviation because of its significant difference with other methods.

• According to Figs. 9(a), 10(a), the storey stiffness is within the acceptable range of mean by using method 2, 3 and 5.



(a) Three-Story Frame



(b) Two-Story Frame

Fig. 14 Standard deviation to mean of storey stiffness for frames with width and Young’s modulus of beams equal to columns and rigid supports; (a) Three-storey frame, (b) Two-storey frame

• In the next step, the ratio of standard deviation to the mean for the models has been calculated. In this study, it is recommended that if the ratio is less than 0.1, the stiffness is not sensitive to the selected method and all methods can be used, if the ratio is between 0.1 and 0.2, the stiffness is sensitive to the selected method and if it is more than 0.2, the sensitivity is high. The presented results in Fig. 14 show in some cases the stiffness is sensitive to selected method and in most cases is high sensitive.

• Due to the fact that the main purpose of calculating the storey stiffness is to control the provision of soft storey in structural design, so then, according to the provision of most seismic codes, the stiffness of first to second storey and second to third storey have been calculated. According to Fig. 15, the ratios are within the acceptable range of mean by using method 3 and 5. In addition, method 1 and 2 are within the acceptable range of mean but, by using method 1, the ratio of second to third storey stiffness is a little less than low range of standard deviation and by using method 2, the ratio of first to second storey stiffness is a little more than high range of standard deviation.

• The less ratio of storey stiffness to the next storey stiffness is, the more reliability it is to detect soft storey. Among the methods that have been within the acceptable range of mean, the least ratio of stiffness in two-storey frames is obtained by using method 1 and the least ratio of stiffness in three-storey frames is obtained by using method 5.

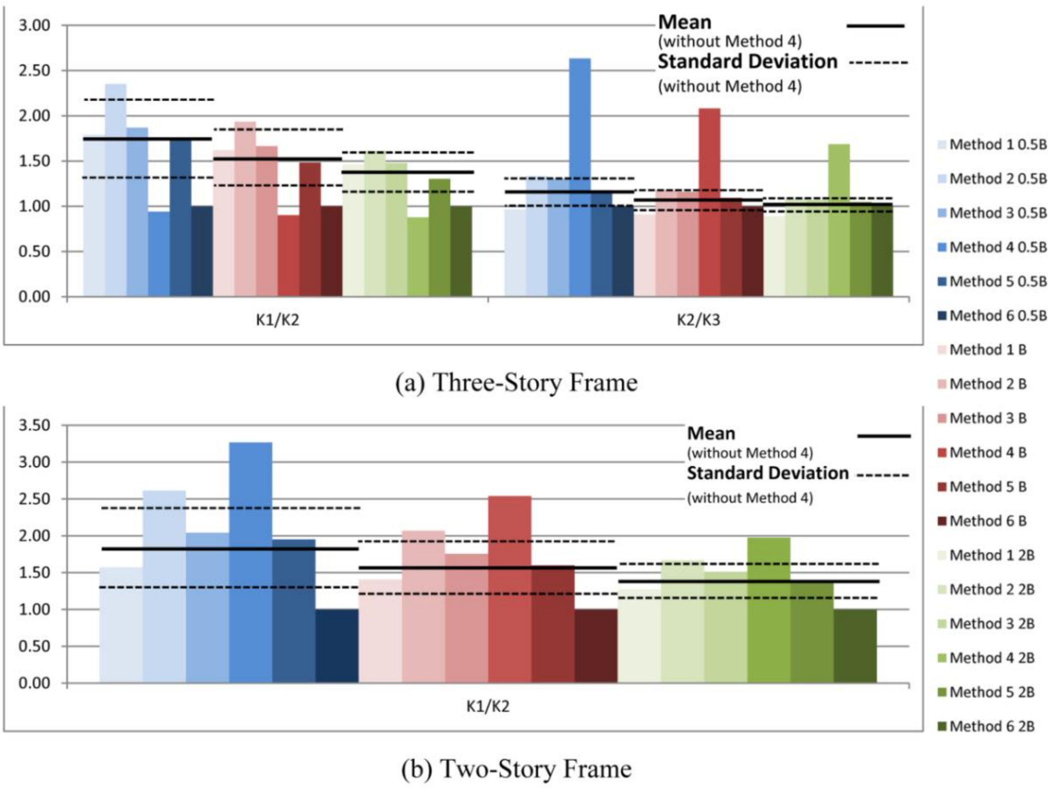


Fig. 15 The storey stiffness to the next storey stiffness for frames with width and Young's modulus of beams equal to columns and rigid supports; (a) Three-storey frame, (b) Two-storey frame

6.3 Structural analysis

Method 1

• In this method, the main structure is not modified, so all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns are considered.

• As in real physical models, storey stiffness is dependent on lateral load distribution, so the obtained stiffness will be different from the actual amount because of difference between load distribution of this method and real earthquake (Fig. 7).

• In 3D models, displacement along the main axis is different from the actual amount because of the torsion created by not being coincident the center of mass of top storey with center of rigidity of other storeys.

• The stiffness of all storeys can be calculated by a single model.

Method 2

• In this method, the main structure is not modified, so all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns are considered.

• As in real physical models, storey stiffness is dependent on lateral load distribution, so the obtained stiffness will be different from the actual amount because of difference between load distribution of this method and real earthquake (Fig. 7).

• As in this method, the force is applied to the center of rigidity of each storey individually, torsional effects that cause changes in the actual amount of displacement along the main axis of the building, will be omitted.

Method 3

• In this method, the main structure is not modified, so all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns are considered.

• As in real physical models, storey stiffness is dependent on lateral load distribution, because of using seismic load distribution pattern in this method, the storey stiffness will be the most similar to seismic forces (Fig. 7).

• The stiffness of all storeys can be calculated by a single model.

Method 4

• In classical finite element method, in order to calculate stiffness in every degree of freedom, all other degrees of freedom are constrained. As a point while calculating storey stiffness in building structures, not only translational degree of freedom is released in that storey, but also rotational degrees of freedom (Figs. 16, 17). All nodes in the storey are released. Therefore it should be noted that there is an “approximation” when this classical approach is used for determining storey stiffness.

• When a complete finite element model is transformed to a simple shear building, a kind of condensation is occurred and all rotational degrees of freedom are removed from the stiffness matrix. However we don’t expect occurring soft storey in the second storey in uniform building, but this approach leads to predict soft storey in second level.

• As it is mentioned, storey stiffness is depending on the lateral load pattern that is not considered in finite element approach (Fig. 7).

• It seems that finite element approach is not suitable for stiffness calculation when soft storey is to be investigated (Fig. 18).

Method 5

• In this method, the main structure is not modified, so all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns are considered.

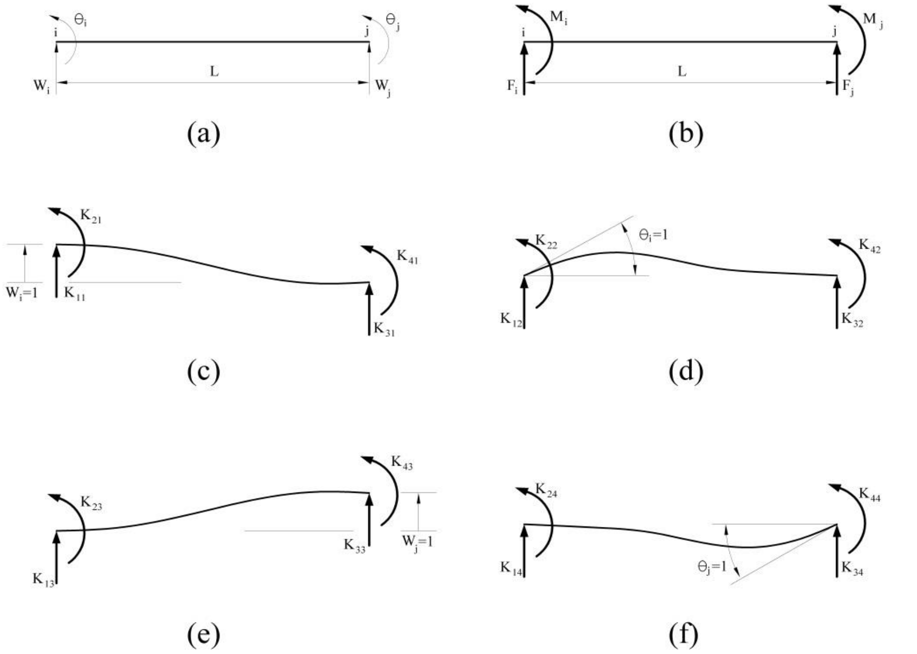


Fig. 16 (a) Four nodal degrees of freedom of a uniform beam, (b) Nodal force and moment, (c-f) Translational and rotational stiffness of each nodal degrees of freedom of a uniform beam

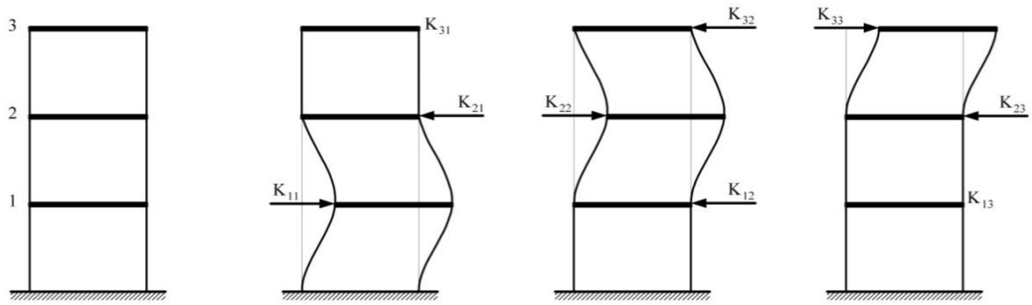


Fig. 17 Finite element model for calculating the storey stiffness

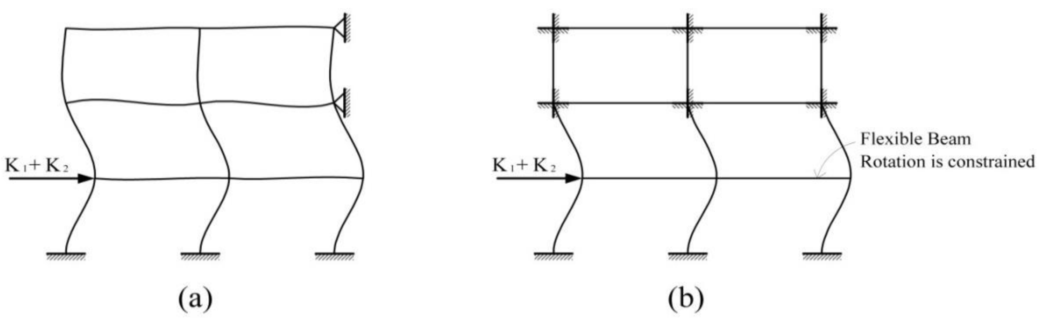


Fig. 18 Finite element model for calculating the storey stiffness; (a) Engineering finite element model, (b) Real finite element model

Table 8 Evaluating calculation methods of storey stiffness based on studied criteria

Criteria	Methods
Not modifying the main structure and considering all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns	1, 2, 3, 5
Using seismic load distribution pattern	3
Simplicity in modeling	1, 3
Being the storey stiffness within the acceptable range of mean	2, 3, 5
Being the ratio of storey stiffness to the next storey stiffness within the acceptable range of mean	3, 5
The least ratio of storey stiffness to the next storey stiffness	1, 5

• As in real physical models, storey stiffness is dependent on lateral load distribution, so the obtained stiffness will be different from the actual amount because of difference between load distribution of this method and real earthquake (Fig. 7).

• As in this method, the force is applied to the center of rigidity of each storey, torsional effects that cause changes in the actual amount of displacement along the main axis of the building, will be omitted.

Method 6

• In this method, by deleting all of the storeys located above the considered storey and defining rigid supports at the bottom of columns, storey stiffness will be changed.

• Due to omitting the above storeys, the stiffness of the above columns won't be considered in the storey stiffness and because of defining rigid supports at the bottom of columns, additional stiffness will be formed in the considered storey. Therefore, contrary to the expectation that in the three-storey structures with the same sections, the stiffness should be reduced by raising the storey, the stiffness of all storeys is the same by using this method.

• Due to defining rigid supports at the bottom of columns, in this method the last storey stiffness will be more than other methods.

Finally results of analysis based on six criteria are presented in Table 8.

7. Conclusions

Despite the expectation of an engineer, it is shown that different calculation methods of storey stiffness lead to completely different answers. It is even possible that in some decision-making processes such as evaluating soft storey to make an error. What is common in engineering society and present in textbooks are method 1 and 4, but it seems that however classical finite element approach to determine storey stiffness can be acceptable when calculating natural frequencies and mode shapes, but it is not suitable for investigating soft storey. Based on the analysis when the purpose is to control the provisions of soft storey and study the behaviour of structure against seismic loads, method 3 as the most appropriate method of calculating the storey stiffness by using structural analysis software is recommended. In this method, the main structure is not modified, so all of the effective parameters on storey stiffness such as support condition, rotation of beams and columns are considered. Due to the sensitivity of real physical models to load distribution, it is significant to use seismic load distribution pattern in this method. It is possible to calculate the stiffness of all storeys by a single model. Therefore, it will be easier to analyze and design the structure by this method. In the term of statistical indicators, the storey stiffness which is calculated by this method and the ratio of storey stiffness to the next storey stiffness is within the acceptable range of mean among discussed methods. The main achievement of this paper is that when the lateral load pattern is specified, the best method for determining the storey stiffness is to apply this load pattern, what is defined in method 3.

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