World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:3, No:2, 2009

Seismic behavior of steel frames investigation with knee brace based on pushover analysis

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Abstract— The knee bracing steel frame (KBF) is a new kind of energy dissipating frame, which combines excellent ductility and lateral stiffness. In this framing system, a special form of diagonal brace connected to a knee element instead of beam-column joint, is investigated. Recently, a similar system was proposed and named as chevron knee bracing system (CKB) which in comparison with the former system has a better energy absorption characteristic and at the same time retains the elastic nature of the structures. Knee bracing can provide a stiffer bracing system but reduces the ductility of the steel frame. Chevron knee bracing can be employed to provide the desired ductility level for a design. In this article, relation between seismic performance and structural parameters of the two above mentioned systems are investigated and compared. Frames with similar dimensions but various heights in both systems are designed according to Iranian code of practice for seismic resistant design of building, and then based on a non-linear push over static analysis; the seismic parameters such as behavior factor and performance levels are compared.

Keywords—seismic behavior, ordinary knee bracing frame, Chevron knee brace, behavior factor, performance level

I. Introduction

In the early of twentieth century, structural engineers realized the potential hazard produced, when strong earthquake happened. Structures designed to resist moderate and frequently occurring earthquakes must have sufficient stiffness and strength to control deflection and to prevent any possible damage. However, it is inappropriate to design a structure to remain in the elastic region, under severe earthquakes, because of the economic constraints. The inherent damping of yielding structural elements can advantageously be utilized to lower the strength requirement, leading to a more economical design. This yielding usually provides the ductility or toughness of the structure against the sudden brittle type structural failure. Since stiffness and ductility are generally two opposing properties, it is desirable to devise a structural system that combines these properties in the most effective manner without excessive increase in the cost. The moment resisting frame possesses good ductility through flexural yielding beam elements, but it has limited stiffness [1]. The concentrically braced frame on the other hand is stiff, however, because of buckling of the diagonal brace its ductility is limited. To overcome the deficiencies in moment resisting and concentrically braced frames, Roeder and Popov [2] have proposed the Eccentrically Braced Frame (EBF) system, where the brace is placed eccentric to the beam–column joint. By a suitable choice of eccentricity, a sufficient amount of stiffness from the brace is retained while ductility is achieved through the flexural and/or shear yielding of a segment of the beam, which is called the link, created by the eccentrically placed brace member. In recent years, Aristizabel-ochoa [3] has proposed a framing system, which combines the stiffness of a diagonal brace with the ductile behavior of a knee element. This system was not suitable for earthquake-resistant design because the brace was designed to slender. Consequently, the brace buckles and leads to pinching of the hysteresis, which is not efficient for energy dissipation. Subsequently, the system has been re-examined and modified by Balendra et al. [4]-[5]. The revised system is called the Knee Braced Frame (KBF). In this system, the non-buckling diagonal brace provides most of the lateral stiffness. The flexural or shear yielding of the knee element provides the ductility under a severe earthquake. In this way, the damage is concentrated in a secondary member, which can be easily repaired at minimum cost.

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II. Non-linear Behaviour Of Knee Brace

Khosravi [6] have demonstrated the nonlinear behavior of the knee bracing under lateral loading in the flexural and shear yielding mode, According to figure. 1 When the suggested lateral load increases gradually, three plastic joints are created on the respective knee element. This causes changes in the total stiffness of structure from K to K0. Finally, a plastic joint in the main frame occurs at joint D. As the shape and form of KBF is optimally selected, three plastic joints on the knee element occur almost simultaneously.

III. Structural Models

In this paper, the performance of a new knee bracing system called Chevron Knee Bracing (CKB) with respect to the similar KBF system is discussed. Therefore, we consider 3, 5, 7 and 9-storey frames for both systems with equal height and bays so that it has been placed in middle bay of the brace. So the number of frames under study is 8. The height of all stories is considered 3 m. There are also 3 bays and length of each bay is 4 m.

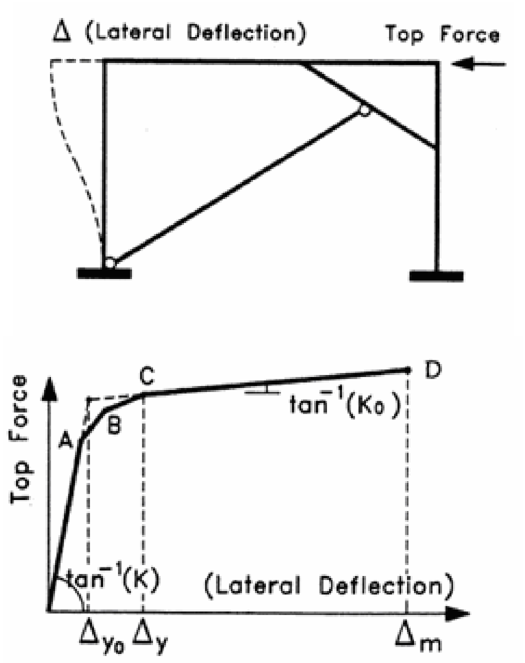

Fig. 1 General non-linear behaviour of KBF against lateral loads.

The best form of knee brace is when the knee element and the diagonal brace are parallel to frame diameter in a way that according to the figure no. 2,3, $h/H = b/B$. In this way the structure has its maximum seismic resistance [7].

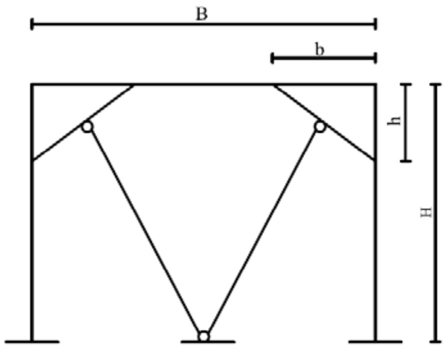

Fig. 2 Situation of knee element in Chevron Knee Bracing

Therefore the situation of knee element and diagonal brace of studied frames have been verified here. In the studied frames the knee element has been placed in the upper storey. Moreover, according to the above mentioned issues, in this article spaces h and b for examined samples are supposed as follow: if we consider $h/H = 0.2$, then we will have:

$$h/H = 0.2 \Rightarrow h = 0.6m$$
$$b/B = 0.2 \Rightarrow b = 0.8m$$

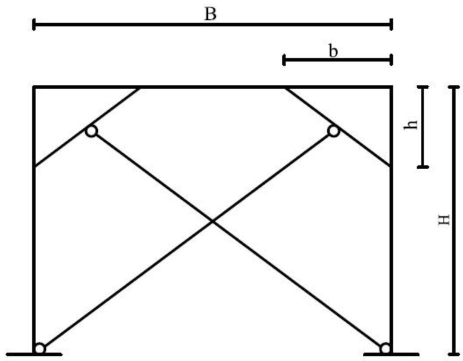

Fig. 3 Situation of knee element in Ordinary Knee Bracing

IV. Design And Analysis

Before analyzing, according to the Iranian loading code the rate of live and dead force have been considered $200\,kg/m^2$ and $600\,kg/m^2$ respectively and then, structures are analyzed and designed by related softwares. Assuming the conditions of area with much relative danger, the type of usage for residential buildings and lands will be of type II and the loading of frames will be done according to Iranian Seismic Code. The type of the steel utilized in frames is of St 37. Yield stress of steel is 2400 kg/m^2 and ultimate stress of steel is $3700\,kg/m^2$, Poison factor 0.3 and modulus of elasticity of steel is $2.6 \times 10^6\ kg/m^2$. After statically analyzing of the structure, it has been designed and specified sections to members in the design have been determined according to table no. I. Situation of connections in frames are considered in two positions according to table no. II.

TABLE I
Specified Dimensions to Members

Knee Brace	Diagonal Brace	Column	Beam	System	Storey
BOX76x5	2UNP12	BOX76x5	IPE24	Chevron	1
BOX127x5	2UNP12	BOX127x5	IPE27	Ordinary	
BOX152x5	2UNP12	BOX152x5	IPE27	Chevron	2
BOX152x5	2UNP12	BOX152x5	IPE24	Ordinary	
BOX127x5	2UNP12	BOX127x5	IPE27	Chevron	3
BOX76x5	2UNP12	BOX76x5	IPE24	Ordinary	
BOX127x5	2UNP12	BOX127x5	IPE27	Chevron	4
BOX127x5	2UNP12	BOX127x5	IPE24	Ordinary	
BOX127x5	2UNP12	BOX127x5	IPE27	Chevron	5
BOX76x5	2UNP12	BOX76x5	IPE24	Ordinary	

TABLE II
SITUATION OF CONNECTIONS

Beam-Column Connection	End of Braced Connection	Knee Beam-Knee Column Connections
pined	pined	rigid

V. CAPACITY SPECTRUM

The methods of designing on the basis of resistance dose not render an appropriate result in most cases because of stating the behavior of structure members through one-parameter resistance. There is no possibility for precise evaluation of structures according to their expected performance in this method. For this reason in the recent years the method of performance-based designing is introduced and performance is focused instead of resistance. This new method of designing determines three main performance levels of immediate occupancy, life safety and collapse prevention for structural members. According to expected level performance in this method, the performance point of structure is determined. There are various methods in the regularities to determine the performance point from which the most important ones are capacity spectrum and displacement coefficients methods. The capacity spectrum method which is used in this article is presented by American institute of ATC in three methods of A, B and C in a way that from A to C the accuracy of the method is being reduced. Therefore, method A [11] which is the most accurate one is used. In this method, intersection point of reduced seismic demand spectrum and capacity spectrum are introduced as performance point of structure which is shown in figure 4.

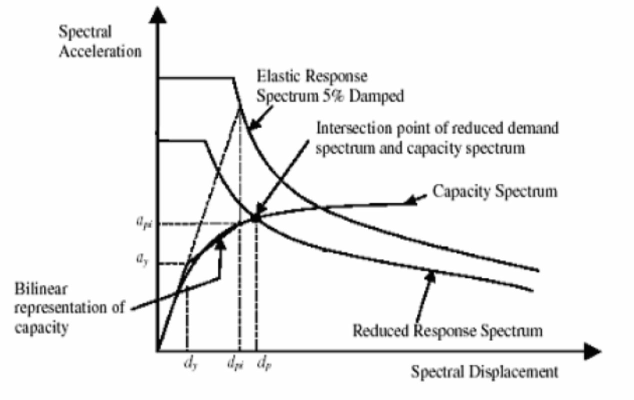

Fig. 4 Demand spectrum and capacity spectrum

Seismic demand spectrum at one risk area is calculated A= 0.35 according to standard spectrum Iranian code of practice for seismic resistant design of building, for basis acceleration of design. The evaluation of seismic performance of frames has been done according to instruction for seismic rehabilitation at life safety performance level. This performance level is studied at one risk level. One Risk level is determined based on probability of 10% incident in 50 years which is equal to return period of 475 years. This risk level in Iranian code of practice for seismic resistant design of building is the same as design earthquake.

VI. PERFORMANCE POINT

After nonlinear static analysis, the capacity curve of frames has been sketched. Then, by using capacity spectrum method which its explanation has been mentioned above. the performance point of studied structures at one risk level has been obtained.

TABLE III
DISPLACEMENT AND BASE SHEAR OF PERFORMANCE LEVEL FOR CHEVRON KNEE BRACING SYSTEM

Base Shear(ton)	Roof Displacement(cm)	Number of Stories
26.3	8.7	3
41.1	16.4	5
55.1	20.6	7
61.3	26.6	9

In order to ease the calculation of structure performance point and to obtain the replacement of performance point through try and error, a program written in Excel has been used. The amount of displacement and base shear such as performance point for chevron and ordinary Knee Bracing system are presented in table no. III and IV. By comparing mentioned tables it is observed that the amount of displacement and base shear such as of performance point for these two systems are different.

TABLE IV
DISPLACEMENT AND BASE SHEAR OF PERFORMANCE LEVEL FOR ORDINARY KNEE BRACING SYSTEM

Base Shear(ton)	Roof Displacement(cm)	Number of Stories
60.7	8.7	3
62.9	4.3	5
82.11	8.7	7
90.8	11.8	9

VII. NONLINEAR STATIC ANALYSIS

In order to do nonlinear statically analysis, nonlinear software has been used. The goal of such an analysis is to verify curve of base shear against the displacement. For this reason, first plastic joint have been allocated to the members in a way that bending joint at two ends for beams, axial-bending joints for columns, axial joint at two ends for braces and bending joint at two ends for knee element are considered. Non-linear joints are used during nonlinear static analysis. The curve of force-displacement of nonlinear joints has been considered according to FEMA 356 instruction. The curve of nonlinear joints will be assigned to each member by help of software. Maximum lateral displacement which is useful for nonlinear statically analysis has been considered as follow according to Iranian code of practice for seismic resistant design of building:

$$\Delta_m < 0.025h \qquad \text{If} \quad T < 0.7s$$

$$\Delta_m < 0.02h \qquad \text{If} \quad T > 0.7s$$

In which T is the main period of structure, h is structure height and Δ_m is maximum lateral displacement. Triangle distribution of lateral force will also be proportionate to stories weight.

VIII. Investigation Of Criteria Of Members Acceptance

After obtaining performance point by capacity spectrum method, this point is considered as displacement of target in order for statically analysis through which level of structure performance can be verified and to prove that where the members are settled in three performance levels after displacement of target. Figure 5 shows created plastic joints in the last step of loading for frames with ordinary braces. The base shear for change of target displacement $\delta_t = 4.2cm$ is 36.2 t and the structure keeps its stability in such displacement and the main members of the structure are in Life Safety level but created plastic joints in forced diagonal braces of first, second and third stories are in an area larger than C and cause them to be failed. Knee elements affected by plastic joints are also placed in LS area and prevent the member from failing. Figure. 6 shows formed joints in 3-storey frames with chevron knee brace. Plastic joints in the mentioned figure are resulted from of target displacement $\delta_t = 8.7cm$. In this system, the plastic joints are created respectively in compression braces of second, third and first stories in a way that the created joints are in an area bigger than C and cause compression braces to fail. Then knee elements face plastic joints without being fail because they are in life safety area or area below that. In this way the main members of the structure such as beam and column remain stable and they are in life safety area. As it can be seen in the above figure plastic joints in members are shown in different colors. Pink shows the area below IO, Blue represents LS-IO boundary. The LS area, Life Safety Zone, is the area we are focusing on, because demand spectrum of Iran Seismic Code 2800 is based on risk level 1. Therefore, on this basis the structure has an appropriate performance when it is within Life Safety boundary. Dark green stands for LS-CP area. The larger area than CP which includes light green, yellow, orange and red indicates that if a member of one these colors affected with plastic joints, the member will be failed.

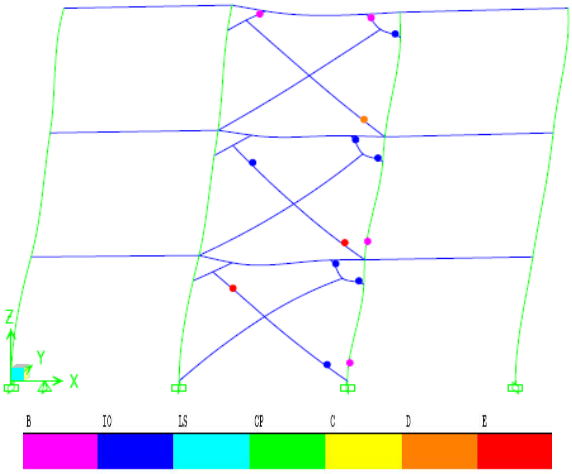

Fig. 5 Plastic joints in three-storey frame with ordinary knee brace

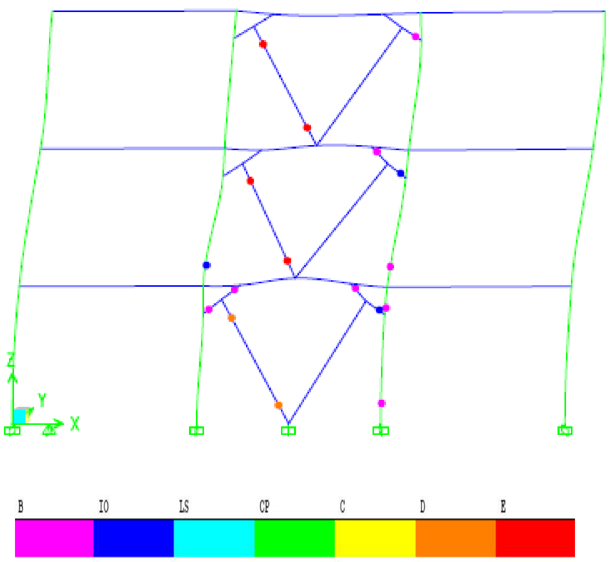

Fig. 6 Plastic joints in three-storey frame with chevron knee brace

A summary of results related to performance of frame's members in risk level 1 are presented in table V and finally, performance of frame's members in 3, 5, 7 and 9 stories frames including column, brace and knee element are specified. Also based on figure no. 7, the knee element performance levels of 7-storeys frames for two systems have been compared. The percentage calculation of members settled in each level is done according to joints creation in the last loading step. In order to show frames abbreviations C and O are used. C stands for chevron And O stands for ordinary. The number next to the letter represents the number of stories in the frame. For example, C3 means chevron knee braces system with 3 storey. Furthermore, all frames have 3 bays. With reference to the table, it is indicated that in frames with ordinary knee braces, whatever the number of stories are more the performance of the columns are better, in a way that in frames O-7 and O-9 100 percent of columns are in the performance level of immediate occupancy. On the contrary, in the frames with chevron knee braces, whatever the number of stories are more the performance of columns are less, in a way that in frames C-7, 50 percent of columns are in the performance level of immediate occupancy and only 10 percent of columns are failed. But in frame C-9 none percent of columns are in performance level of immediate occupancy and 28.5 percent of columns are failed.

TABLE V
PERFORMANCE OF FRAMES MEMBERS WITH CHEVRON AND ORDINARY BRACES

Percentage of assigned members to each performance level on the basis of risk level 1				Frame	Member
>CP	LS-CP	IO-LS	IO>		
		25	75	C3	Column
	14.25	14.25	71.5	C5	
10	10	30	50	C7	
28.5		71.5		C9	
			100	O3	
		16.7	83.3	O5	
			100	O7	
			100	O9	
100				C3	Diagonal Brace
100				C5	
100				C7	
100				C9	
60		40		O3	
37.5		37.5	25	O5	
50		50		O7	
50		50		O9	
		28.5	71.5	C3	Knee
	12.5	37.5	50	C5	
22.2		55.5	22.3	C7	
45.5		45.5	9	C9	
		71.5	28.5	O3	
75			25	O5	
37.5	37.5		25	O7	
50	25		25	O9	

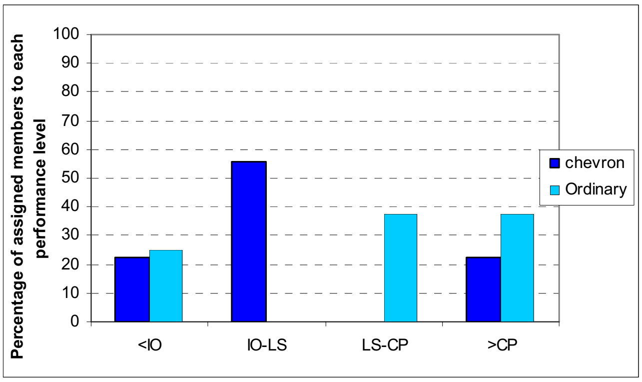

Fig. 7 knee element performance levels of 7-storeys frames

IX. Seismic Parameters

Uang [8] proposed a simplified procedure to estimate the response modification factors, in which the response modification factor, *R*, is calculated as the product of the three parameters that profoundly influence the seismic response of structures:

$$R_w = R_\mu . \Omega Y \tag{1}$$

Idealizing the actual structural response curve by the linearly elastic-perfectly plastic curve in Figure. 8, the structural ductility factor can be defined as:

$$\mu = \Delta_u / \Delta_y \tag{2}$$

With reference to Figure. 8, in which the actual force – displacement response curve is idealized by a bilinear elastic–perfectly plastic response curve. Structure has a capacity to dissipate hysteretic energy. Because of this energy dissipation capacity, the elastic design force can be reduced to a yield strength level *(V_y)* by the factor R_μ :

$$R_\mu = V_e / V_y \tag{3}$$

The reserve strength that exists between the actual structural yield level *(V_y)* and the first significant yield level *(V_s)* is defined in terms of the overstrength factor R_s :

$$R_s = V_y / V_s \tag{4}$$

From Figure. 8, the total force reduction factor corresponding to the strength design format (UBC-1997, IBC-2000, NEHRP-2000*)* can be derived as follows:

$$R_u = \frac{V_e}{V_y} . \frac{V_y}{V_s} = R_\mu . \Omega \tag{5}$$

By nonlinear analysis, seismic parameters such as behavior factor can be calculated. After nonlinear static analysis capacity curve is sketched. By the help of such a curve the amount of base shear can be determined according to the first plastic joint and final disjoint of structure. After verifying capacity spectrum graph through nonlinear static analysis, the numerical amount of base shear and its displacement can be obtained. Then by using related software on the basis of energy method, amount of V_y and Δ_y are obtained. Energy method is a method for determining base shear V_y and displacement Δ_y according to general sketch of the structure and resulted by bilinear the capacity curve so that level below capacity curve equalized with bilinear graph As it was mentioned in part two, one of the important factors in behavior factor is deduction coefficient resulted from formation. Up to now various relations for determining resistance modification factor resulted from R_μ have been suggested [9]. From among these relations, Miranda relation is the most comprehensive one for determining modification factor resulted from ductility because not only involve recurrence time, but also include land type and earthquake velocity [10]. In this article Miranda relation has been used to determine R_μ.

$$R_\mu = (\mu - 1)/\phi + 1 \qquad (6)$$

μ according to relation (2) and ϕ in the following equations are obtained for stony and sedimentary grounds and soft soil grounds respectively. In this article for calculating coefficient of ϕ the related equation is used.

$$\phi = 1 + \frac{1}{12T - \mu T} - \frac{2}{5T}\exp\left[-2(\ln T - \frac{1}{5})^2\right] \qquad (7)$$

$$\phi = 1 + \frac{1}{10T - \mu T} - \frac{1}{2T}\exp\left[-3/2(\ln T - \frac{3}{5})^2\right] \qquad (8)$$

$$\phi = 1 + \frac{T_g}{3T} - \frac{3T_g}{4T}\exp\left[-3(\ln\frac{T}{T_g} - \frac{1}{4})^2\right] \qquad (9)$$

T_g is the dominant period of earthquake, i.e. a period in which the maximum relative speed of a linear elastic system with 5% damping throughout boundary of periodic changes is maximum. The calculations of seismic parameters of studied frames are presented in
tables no. VI and VII. Also to compare the ductility factors, overstrength and behavior factor between two systems, column diagram has been drawn according to figure no. 9 and 10 and 11.

TABLE VI
SEISMIC PARAMETERS OF ORDINARY KNEE BRACING SYSTEM

Number of Stories	μ	R_s	R_μ	R_u
3	1.85	1.8	1.7	4.3
5	2.8	1.6	3.1	7
7	3.4	1.5	4.2	8.8
9	4	1.4	4.7	9.2

X. DISSIPATING OF ENERGY

As we know force or energy is equal to level below force-displacement graph. Therefore having capacity curve, measurement of area under graph can be calculated. This measure is stored energy in the structure. In designing buildings resistant against earthquake if a building absorb more energy before collapsing it is more flexible and desired on structural point of view. The amount of energy absorption of Chevron and ordinary Knee Bracing system figure no. 8.

TABLE VII
SEISMIC PARAMETERS OF CHEVRON KNEE BRACING SYSTEM

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3	1.85	1.8	1.7	4.3
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7	3.4	1.5	4.2	8.8
9	4	1.4	4.7	9.2

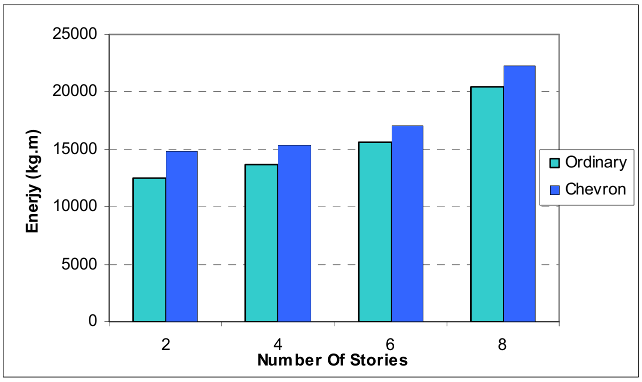

Fig. 8 Amount of stored energy in frames

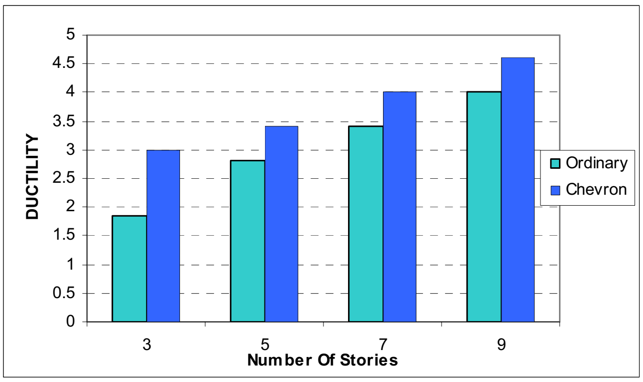

Fig. 9 Comparison of ductility factors in frames

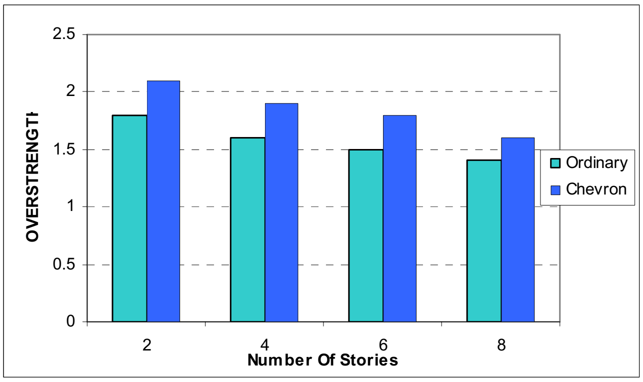

Fig. 10 Comparison of overstrength factors in frames

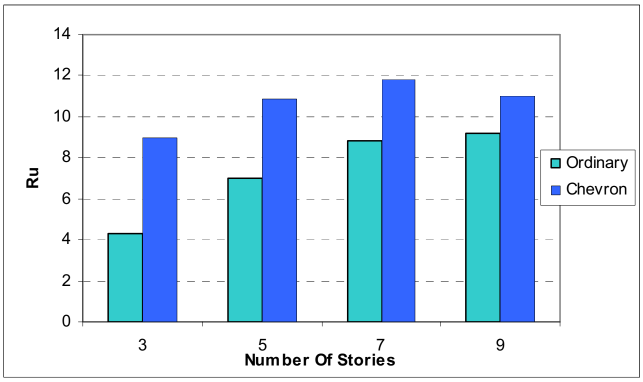

Fig. 11 Comparison of behavior factor in frames

XI. Conclusions

By examining and studying mentioned models, following results have been obtained:

1. Comparing both systems according to table 5, it seems that the performance of columns in ordinary knee braces system is better than the one of chevron knee braces system, because according to the results the column collapse and structure instability is more probable in chevron knee braces system.

2. Since brace and knee members are considered as secondary members of the frame, in mechanizing process of frames, as it was expected, first braces and then knees are affected by plastic joints and they are failed. This happens in a way that the braces lose all their performance and knee members set in life safety level for an extent. Therefore, it can be concluded that most of the models have appropriate performance level in risk level 1.

3. According to calculation of behavior factor for both systems, it is clear that by increasing the number of stories, the rate of this factor will be increased. The value of behavior factor for ordinary knee braces system can be considered $R_u \approx 7.5$ and for chevron knee brace system considered $R_u \approx 10.5$.

4. By studying tables related to seismic parameters it is proved that whatever the stages in creased the overstrength factor reduced and also the ductility factor are increased

5. The amount of dissipating and energy absorption in chevron knee braces system is more than ordinary knee braces system which indicates high ductility of chevron knee braces system against stiffness of ordinary knee braces system.

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