

Evaluating Seismic Capacity of Steel Frames with Knee Bracing

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Abstract

Knee Braced Frames (KBF) is a new system of energy dissipation in steel frames which provides good combination of ductility and lateral hardness. In KBF, at least one end of brace connects to the brace member which locates between beam and column sidelong instead of connecting to the beam-column junction. Coaxial bracing supply hardness of system while ductility is obtained under influence of lateral loads through knee member flow. When earth quack happens, knee member acts as ductile fuse and prevents coaxial bracing buckling and energy dissipation happens through bruised of knee member. In this study, we investigate three buildings (3, 5 and 7 story ones) of 2 types (3 and 5 bays) with coaxial bracing, chevron, moment frames, and knee braces through non-linear static analysis in uniform lateral load distribution and the first mode of vibration. Also concentric bracing, chevron and moment frames performance in construction frames in comparison with knee bracing frames is discussed. As an energy dissipating system, Knee bracing frame has a combination of excellent ductility and lateral stiffness that has a high performance against lateral loads, especially earthquake.

Keywords: moment frame, knee bracing, level of performance, non-linear static analysis, x bracing

Introduction

In 1986, designer engineer named Aristizabel-Ochoa had introduced Steel a system called disposable knee bracing. The end of brace connects to the point of knee member which locates between beam and column or column and support instead of connecting to the beam and column junction[1,2]. bracings are one of the systems that resist lateral forces and show a good seismic performance like

reduced inter-story drifts. [1, 2] no sway structures induce high lateral stiffness and considerably reduce structure drift against seismic loads. However, some engineers tend to use divergent braced frames, but in practice, usage of convergent braced frames is highly increased. [3] X bracings induce to design structures for higher base shear by development of high stiffness, but they are still more economical than moment frames. This frames start to lose compressive strength and cause to concentrate damage in weaker stories by entering the non-elastic area. [2] Also one the most important deficiency of this system is buckling of the bracing. On the other hand, a convergent bracing system with knee members is recommended [4], that prevents from bracing buckling and knee element acts as a fuse and dissipates earthquake forces or lateral force by creating plastic hinge. [5] In recent years, usage of this systems has been research topic of many engineering science researchers. [8, 6]

Evaluated systems

Analyzed frames including moment frames, normal frames with chevron bracing, knee bracing, x bracing in three levels which are 3-story, 5-story and 7-story and three and five 5-meter bays have been evaluated. Story height of all models has considered 3 meters. Allowable stress of steel materials 2400 , ultimate stress 3700 , expected yielding strength of this steel 2640 and ultimate expected strength 4070 have been considered. Structures are designed according to UBC97, [10] 6th code is used for gravity loading and 2800 code for lateral loading. Dead load for all stories 550, live load for stories 200 and for roof 150 has been considered. The load width of this frames is assumed 3 meters for these frames.

For simplifying, equivalent terms is used for each models.

3 stories, 3 bays with x bracing model (X-brace 3St-3B)	5 stories, 3 bays with knee bracing model (Knee 5St-3B)
3 stories, 3 bays with knee bracing model (Knee 3St-3B)	5 stories, 3 bays with chevron bracing model (Chevron 5St-3B)
3 stories, 3 bays with chevron model (Chevron 3St-3B)	7 stories, 3 bays with x bracing model (X-brace 7St-3B)
3 stories, 3 bays , Moment model (M 3St-3B)	7 stories, 3 bays with knee bracing model (Knee-brace 7St-3B)
5 stories, 3 bays with x bracing model (X-brace 5St-3B)	7 stories, 3 bays with knee bracing model (Knee 7St-3B)
5 stories, 3 bays with knee bracing model (Knee-brace 5St-3B)	7 stories, 3 bays with knee bracing model (Chevron 7St-3B)

5 stories models has been determined like 3 stories models with one difference, 3B has been changed to 5B.

For primary analysis and design of frames, ETABS and for seismic evaluation with non-linear static analysis SAP 2000 have been used. In designing models, the status of joints will be as follows: beam-column joints in the form of rigid, joints of the knee element to beam and column in the form of rigid, joints of diagonal bracing to the knee element and to the column as well as the joint of column leg as hinge. Knee elements has been designed considering moment yielding, so Eq.1 should be satisfied in all knee elements.

$$1) L_{min} \geq 4M_p/V_p$$

Where:

Least length of knee element, = section plastic moment, = section plastic shear

To compute, Eq.2 and Eq.3 have been used.

$$2)) M_p = Z \cdot F_y$$

$$3) V_p = t_w (d - t_f) \frac{F_y}{\sqrt{3}}$$

Where:

Z= plastic section modulus, = steel yield stress, = web thickness, = flange thickness, d= section height

For example, knee calculation with section HSS4x4x1/2 has been showed.

Knee bracing situation

According to experiments taken in previous investigations [11] the best angle to install knee element is parallel to diagonal bracing, so is considered. (fig1) also it is recommended to consider. To simplify the model and based on the indicated limitations, all knees has been considered with 115 cm length, h=60 cm and b= 100 cm.

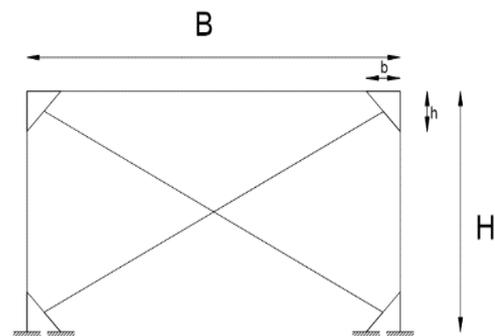


Fig1. Diagonal knee braced frame (KBF)

Plastic hinge properties introduction

In non-linear static analysis, plastic hinge properties should be related to structures elements. [12] In this level, because two ends of beams in braced frames are hinge, plastic hinges is allocated to middle of beams because of their possibility to develop. In columns, this plastic hinges has been determined in ends of columns that is similar to fact.

Plastic hinges of axial forces in middle of bracings have considered cording to ultimate compressive strength. Also for knee elements, according to consideration of their moment behavior, moment plastic hinges has considered in start, middle and end on knee element. Because plastic hinges in steel structures approximately spread to a length as long as section depth and in SAP 2000 plastic hinges is determined as point, so possible point for development of plastic hinges has been considered in 0.05 L and 0.95 for columns.

In non-linear static method, instead of experiment or analysis results, it is allowed to use force-deformation curve given in fig2 with a, b and c determined in FEMA356 [9] for steel frames. Also rotation or deformation corresponding to different levels of performance in elements which are controlled by deformation is introduced in this table. Slope of strain stiffening effects is considered Equivalent to 3% of elastic slope. Considering higher slope for strain stiffening part, only is allowed in experiments that is not evaluated in this

investigation. Q and parameters in fig3 shows generalized force and strength of first yielding of element, respectively. In beams and columns, θ means all elastic and plastic rotation of beam or column, θ_y yielding rotation, Δ all elastic and plastic deformation and Δ_y yielding deformation. Also fig3 indicates rotation of the line between end and start of beam.

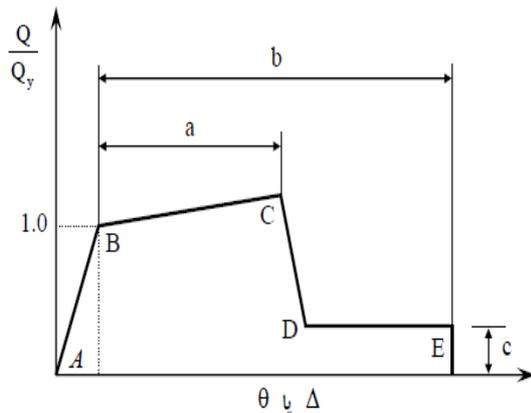


Fig2. Force-deformation curve for steel members [9]

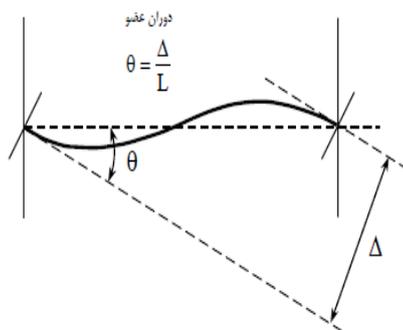
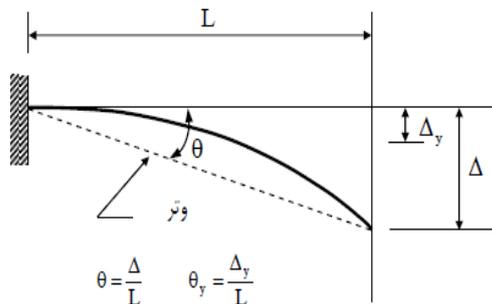


Fig3. Element rotation definition [9]

In beams, θ_y is calculated by Eq4 and in columns by Eq5

$$4) \quad \theta_y = ZF_{ye}L_b/6EI_b$$

$$5) \quad \theta_y = ZF_{ye}L_c/6EI_c[1-P/P_{ye}]$$

Where:

E= Modulus of Elasticity, Z = expected stress for element yielding, I= Moment of inertia, L= Beam Length, Lc = Column length, P= axial force of element is goal deformation,

Z = expected axial force for element yielding

To define plastic hinges in beams and columns, slender restrictions have an important role in level of performance definition and section plastic strength. This issue induce plastic hinges not to be chosen automatically by the software. So for all used sections in this investigation, plastic rotation values is calculated and their parameter is allocated to plastic hinges by FEMA 356 requirements. Seismic parameters is obtained ACCORDING TO IRANIAN 2800 STANDARD for soil type II and area with high seismicity (A=0.3)

According to FEMA 356 and improvement manual, improvement levels are depended on level of performance and seismic danger. Response spectrum design is considered on level of seismic danger 1 that is considered for design in IRANIAN 2800 STANDARD.

Evaluation with non-linear static analysis

Because of the simplicity, non-linear static methods are one of most common analysis tools and they indicated an effective graphic show from general structure response by pushover curve. [13, 14] this curve is directly related to system capacity that is usually defined by base shear with the response of a very significant structural node (control node). This kind of general response of structure allows to directly idealize from structure as single degree of freedom that really simplify design and evaluation. [15,16] in this part, non-linear static analysis is used to compare mentioned bracings for evaluating system capacity, safety factor, maximum relative displacement in stories and also maximum shear created in stories.

Lateral load distribution

As recommended for structures improvement in 360 magazine, lateral load distribution should be similar to what happens in earthquake. So at least two kinds of lateral load distribution should apply to structure. In this part a distribution corresponding to the first mode of vibration in the desired direction as the first pattern of lateral load has been utilized. Uniform load distribution in structure height is used for second load combination.

6-1. applying gravity load

While evaluating structure against lateral loads, It should be considered to apply lateral load and gravity load simultaneously, so first structure against gravity loads should be analyzed with non-linear method, then, lateral loads applies to structure while gravity loads exists. According to available buildings improvement manual, high and low limit of gravity load effects (Q_G) is calculated by following equations.

6) $Q_G = 1.1(Q_D + Q_L)$

7) $Q_G = 0.9Q_D$

Where:

Structure Lateral load capacity evaluation by capacity curve

Non-linear static analysis by applying lateral load with first and second load combination that is defined in improvement manual, is performed and capacity curve of evaluated structures is achieved. Vertical axis of this curve shows value of base shear in non-linear static analysis. Horizontal axis of this curve shows general drift of structure, in other words, rate of control point drift (roof drift). Following figures shows mentioned structures capacity curves.

3 stories structures capacity curves against lateral load is shown in fig4. As it's obvious, the area under capacity curve in short moment structures has higher value and this system has more ability to dissipate energy than other evaluated systems. After that, knee braced frame capacity curves had better behavior than others, because of its higher value of area under curve. As can be seen, primary slopes of this curves have higher value than moment frames that shows higher primary stiffness of braced structure. So structures should be designed for higher base shear value. Anyway, existence of appropriate ductility and stiffness can leads the structure to dissipate energy and withstand logical relative drifts.

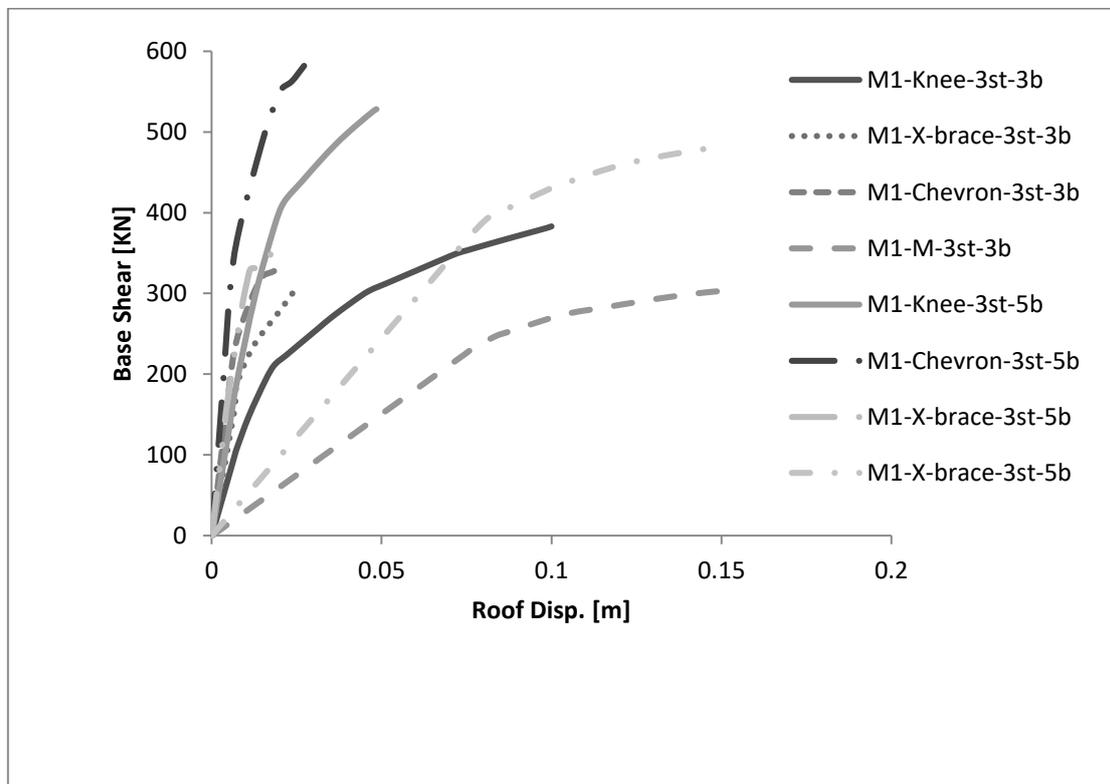


Fig4. 3 story Structure capacity curve in first load combination.

Figure 5 shows results of figure 4 under uniform load combination. As can be seen, this figure approves the results of the previous figure. Generally, this figures show that performance of x-

braced frames and chevron braced frames are not well, because of most primary stiffness and low tolerance against drifts.

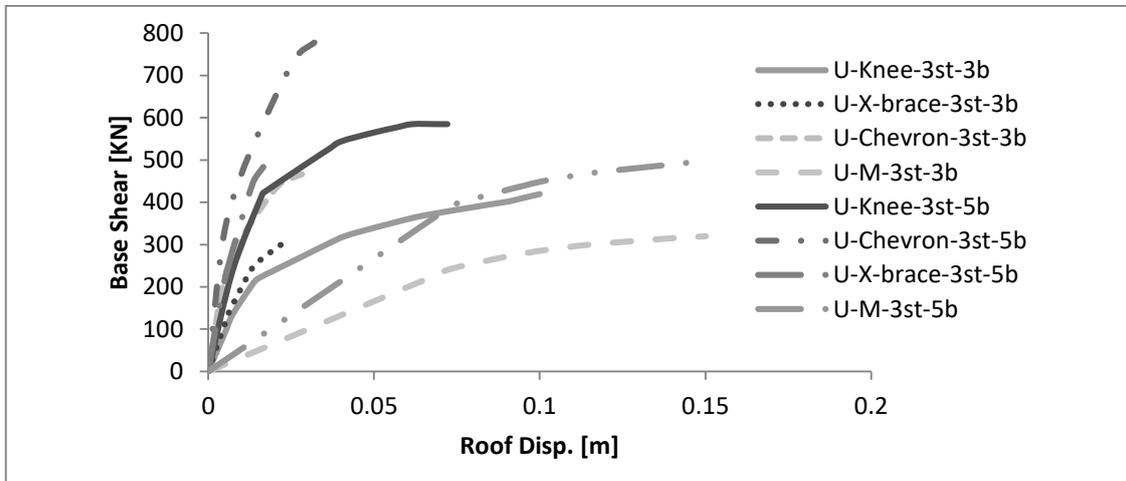


Fig5. 3 story Structure capacity curve in uniform load combination

According to figure 6, it can be understood that distance between moment structure and braced structure capacity curves is increased. This issue indicates that braced systems performance in this height zones is higher. Generally, this results

approves previous results too. In this height zones, braced structures faces intensive strength downfalls. This issue can relates to bracing destruction in one story, soft story development and general structure destruction.

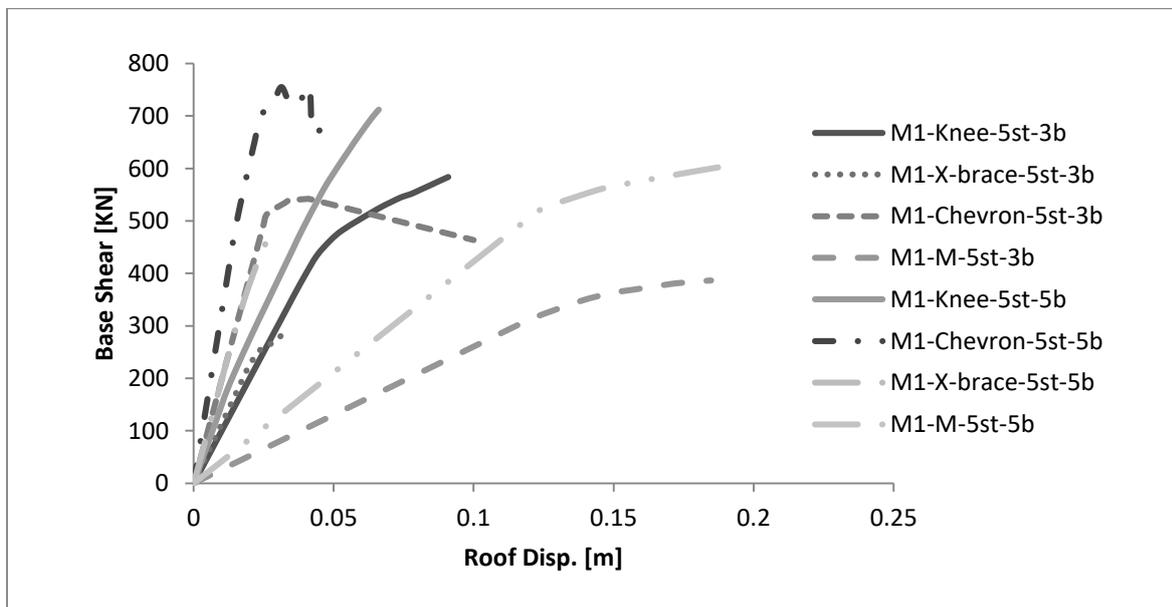


Fig6. 5 story Structure capacity curve in first mode load combination

Figure 7 has shown results related to 5 story structures under uniform load combination. This figures also approves results related to first mode

load combination. Anyway, structure evaluation under uniform load combination shows higher value of structure capacity.

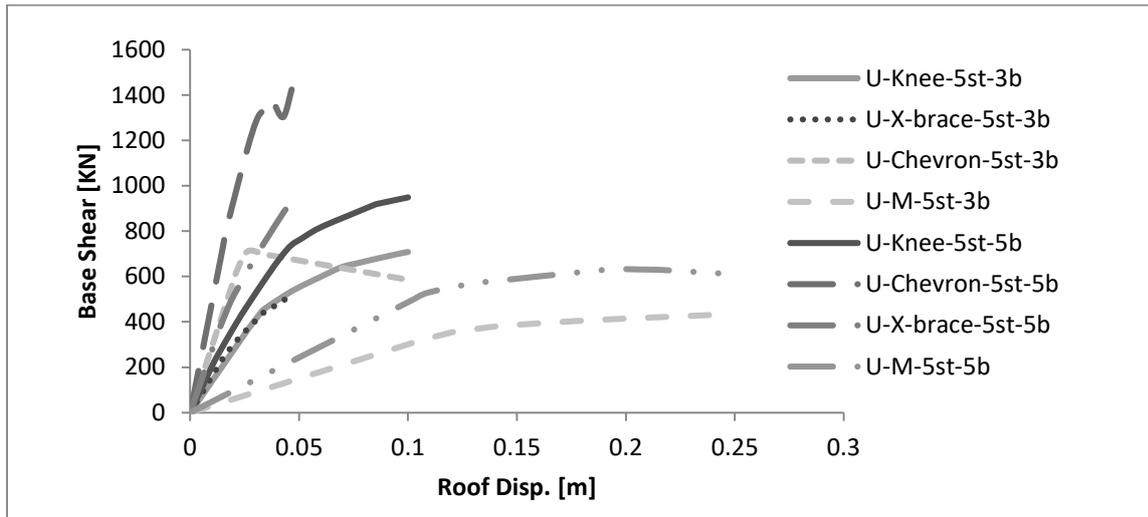


Fig7. 5 story Structure capacity curve in uniform load combination

According to fig8, values of structure capacity curves of knee bracing with adequate stiffness have more strength of relative displacements reduction than moment structures. Also this figure has covered

bigger area than braced structures.

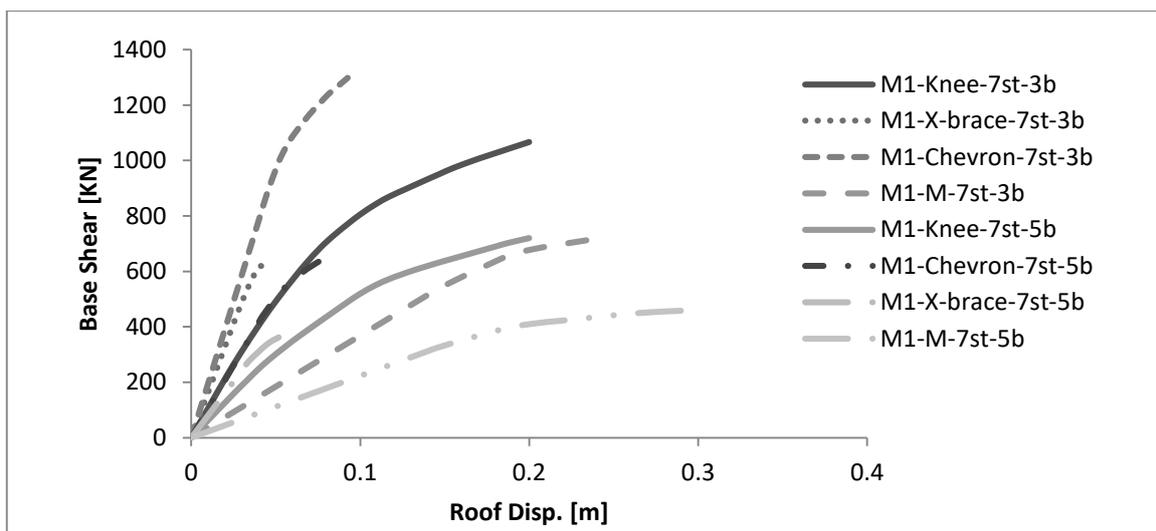


Fig8. 7 story Structure capacity curve in first mode load combination

Figure 9 has shown 7 story Structure capacity curve under uniform load combination. As can be seen, performance of knee bracings is acceptable in this

height zone and have better ductility than other bracing systems.

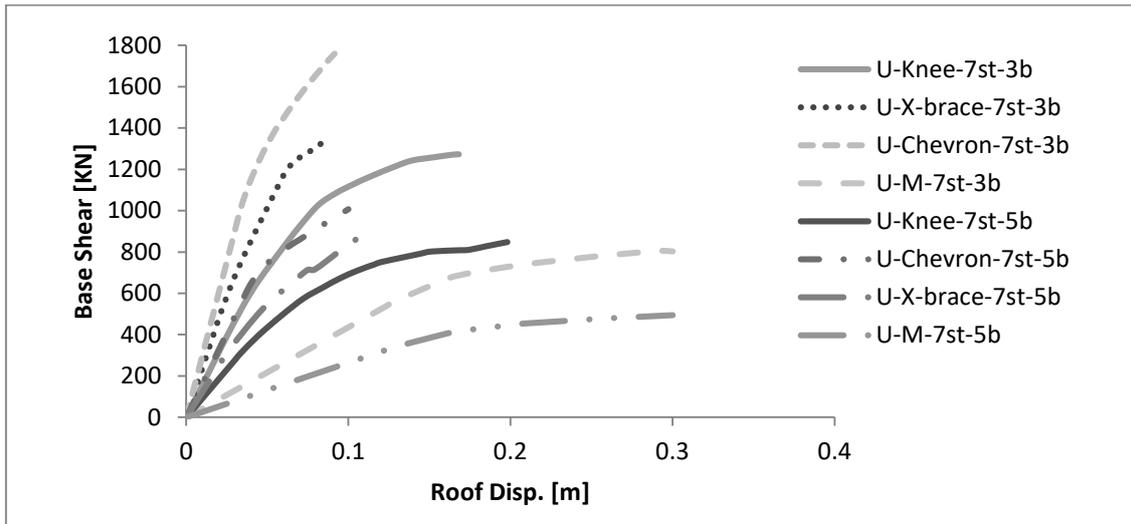


Fig9. 7 story Structure capacity curve in uniform load combination

Figures 4 to 9 showed structure capacity curve or pushover curve of 3, 5 and 7 story structures. In these figures, structures response under lateral load combination model and under uniform load combination is shown. As can be seen, knee braced structures have lateral load capacity similar to x-braced. But, in these structure, especially in 3 story structures, knee bracing have better ductility than x bracings. Ductile performance of knee bracing is one of other points of this figures. In this situation, structure have lower lateral stiffness, so dominant period of structure increases that induces to design structure for lower base shear.

Stories relative displacement evaluation

In following figures, only permanent relative displacements when structure has led to its target displacement is evaluated. Figure 10 shows drift curve of 3 bay- 3 story structures under two load combination. As was expected, moment structures have higher ductility while tolerate bigger drifts that can lead design result to displacement control design. Although chevron bracing have lower drifts, but this structure faces bracing destruction under small displacements, and their destruction limit is in lower displacement and at that moment have lower drift than knee bracing. This issue can be evaluated by structure ultimate displacement control in comparison to roof displacement in target displacement point.

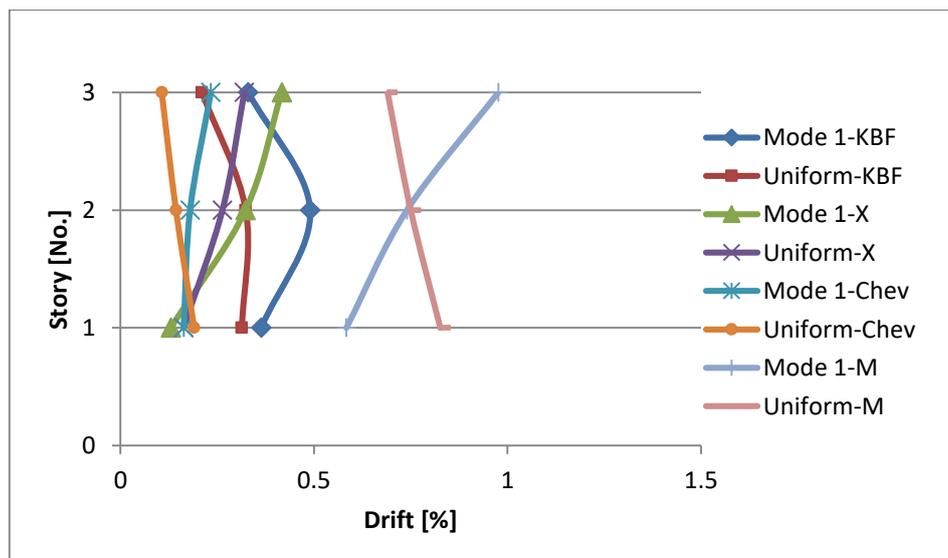


Fig10. Drift curve of 3 bay- 3 story structures under two load combination

Figure 11 shows maximum structure drift for 3 bay- 5 story structures. This figure has approved previous

results too. Comparing the results of figures 10 and 11, we can understand that with such a range of

increase in height the drift curves of most stories will be similar.

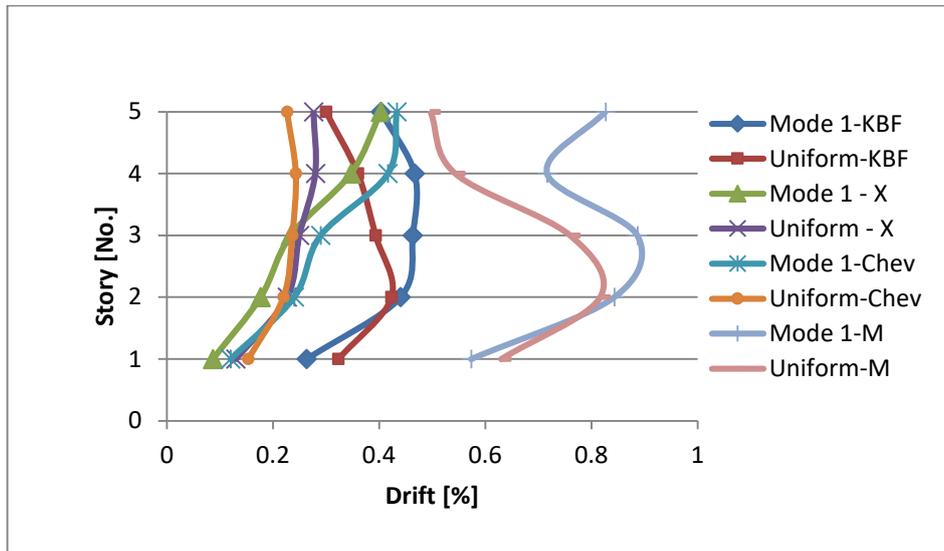


Fig11. Drift curve of 3 bay- 5 story structures under two load combination

Figure 12 approved previous results too. Generally, more ductility the structure have, more story drifts it tolerate. Therefore, as can be seen in this figure, x

and chevron braced structures have the least values and knee bracings have the most values.

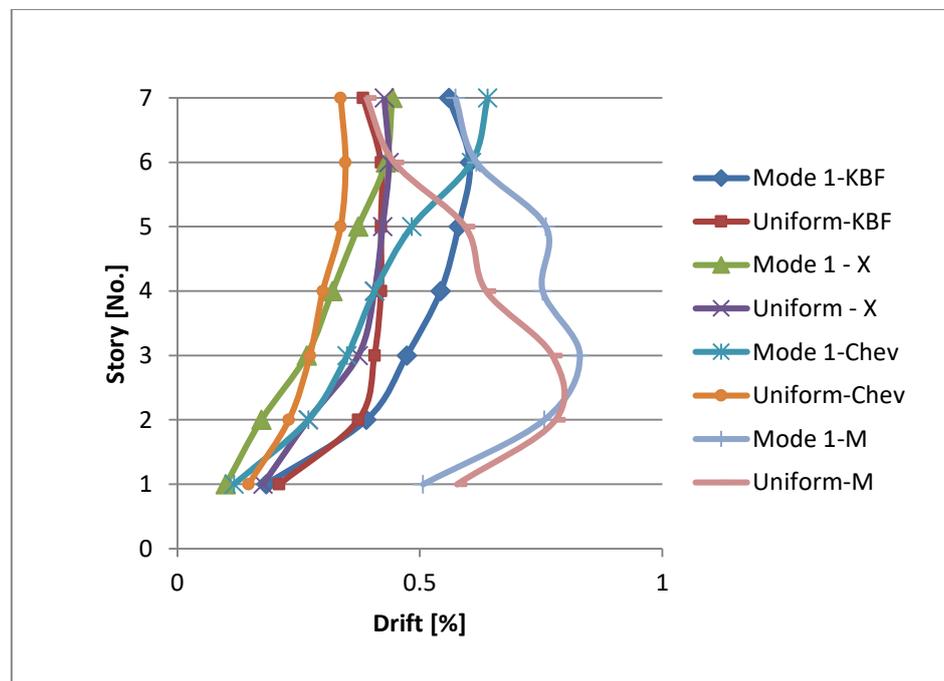


Fig12. Drift curve of 3 bay- 7 story structures under two load combination

Figures 13 to 15, shows maximum drifts for 5 bays structures. General procedure of this curves shows similar results of maximum drifts. As can be seen, results achieved from 3 bays structures have similar

procedure to 5 bays structures. So existence of 2 bays doesn't have an important effect on bracing system behavior.

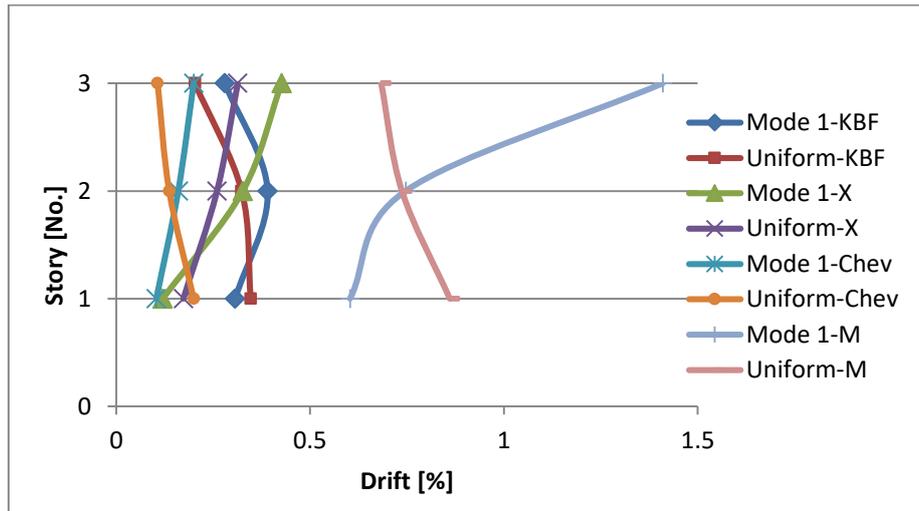


Fig13. Drift curve of 5 bay- 3 story structures under two load combination

Figure 14 shows drift values of structure for 5 bays – 5 story structures. One of important parameter in performance evaluation of a system is to indicate a uniform procedure of maximum structure drift. As

it's shown, moment structures and x-braced structures couldn't indicate a uniform procedure of maximum structure drift. Chevron braced structures and knee braced structures shows better curves.

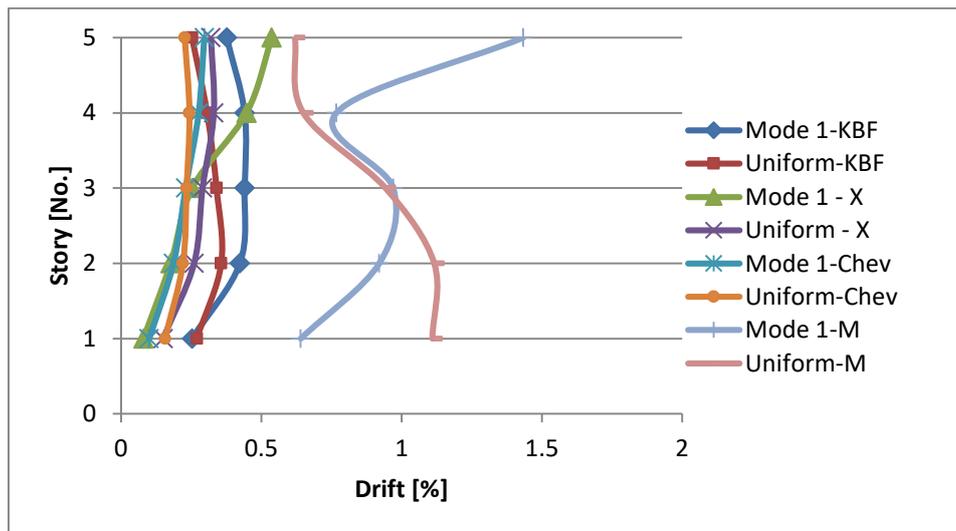


Fig14. Drift curve of 5 bay- 5 story structures under two load combination

Figure 15 shows results achieved from 5 bays - 7 stories structures. As it is obvious, drift curve of x-braced structures have a high Elongation in the middle of way that can cause to general collapse of

structure or inappropriate high deformations by destruction of bracing of that levels. Other bracing systems show similar results.

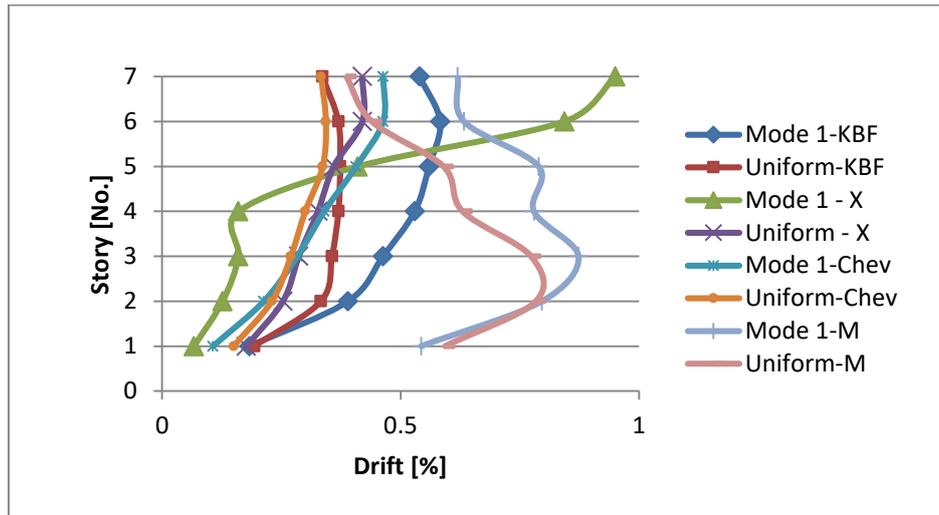


Fig15. Drift curve of 5 bay- 7 story structures under two load combination

Figures 10 to 15 show relative displacement of stories in structure height in target displacement of structure. As it is obvious, because of their higher ductility, knee braced structures experience much

Results

To have better perception of knee braced structures, steel frames including moment frames, knee bracing, x bracing and chevron bracing in three levels which are 3, 5 and 7 stories is evaluated. In this investigation, lateral capacity of steel structures and relative drift values have been evaluated. Results showed that knee braced structures have better energy dissipation and higher ductility than other bracing systems and can be designed for lower base shear values. Anyway, knee braced structures should withstand bigger drifts and inelastic displacements that needs more accuracy in design based on displacements.

Knee elements induce to develop plastic hinges in knee element before moment bracing and decrease bracings destruction. Primary slope values of lateral capacity curve for this structure is less than x bracings. So because of less base shear values for designing of knee bracing, consumption of steel is reduced.

1. Elastic lateral stiffness of KBF frames is less than CBF frames. So KBF frames will be designed for lower base shear.
2. Lateral displacement of KBF frames is more than CBF frames. So KBF frames have worse seismic performance than CBF frames against earthquake force for lateral displacement.
3. Because of development of ductile fuse, Knee element in KBF frames has an sharp drop after yielding, so energy dissipation occurs for development of plastic moment hinges and damages to a small part of structure that is easy to fix or

displacements and drifts. As expected, by developing knee in start and end of bracings, knee bracings shows more ductile behavior and displacements than x-bracing.

replace. So in this case, KBF frames are better than CBF frames.

4. KBF frames ductility is more than CBF frames.
5. Use of knee braced frames can improve frame performance.

Generally, knee braced system is one kind of bracing systems that depend on effective parameter selection can provide excellent stiffness and ductility for the structure and after earthquake, can be used again by knee element replacement.

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