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Investigation of Deformability of Steel Structures with Concentric Braced Frames

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ABSTRACT

In the past, the structures were designed according to their elastic response. This issue cause increasing dimensions of sections and therefore results in many economic and practical problems. For lessening these problems, the codes have been looking for a proper solution. The researches indicated when accounting deformability and energy dissipations of the structures, seismic load could be reduced in a significant degree because of occurring plastic hinges and inelastic behavior of the structure. Therefore, the seismic design criterion that is presented in codes is according to deformability of structures. In this paper inelastic behavior of structures with steel concentric braced frames (CBFs) for two four and eight story models are evaluated by pushover analysis with the SAP2000 software. The results indicate that with special plans like changing the dimensions of sections in use and modifying the process of forming plastic hinges in structure, the inelastic behavior of the structure could be improved significantly. The main purpose of the nonlinear static procedure is focusing on effective nonlinear parameters in analysis and following many advantages that there aren't in linear analysis such as : exact evaluating of force, deformability in structural and nonstructural elements, deterioration of strength, critical areas of structure, route of force and else (as is mentioned subsequently).
KEYWORDS: Pushover, plastic hinge, inelastic behavior, deformability.

1- INTRODUCTION

The performance of different structural systems when occurring high seismic loads is one of the most important issues that a design engineer should be acquainted perfectly in order to design structures that have a high safety factor against seismic loads. The structures are usually designed according to their elastic strength. The analyses indicated that the assumption of elastic response of materials lead to increasing loads on the elements of a structure. This assumption cause increasing dimensions of sections. The researches express those structural elements with nonlinear response cause absorption and then dissipation of energy [14]. This cause reducing the dimensions of sections used in designing.

2-The purposes of seismic design of structures

The purposes in the seismic design of structures are as follows:

- In low seismic ground motions (the ground motions with the 50 percent probability of being exceeded in 50 years the lifetime of the structure) that occur frequently in the lifetime of structures, the structural and nonstructural damage shall be prevented.
- In moderate seismic ground motions (the ground motions with the 10 percent probability of being exceeded in 50 years the lifetime of the structure) that occur sometimes in the lifetime of structures, the structural damage shall be prevented and nonstructural damage shall be minimized.
- In major seismic ground motions (the ground motions with the 10 percent probability of being exceeded in 100 years the lifetime of the structure) that occur scarcely in the lifetime of structures, major structural damage shall be prevented.

In the conditions that secondary effects of earthquake like flood and fire… and effects like surface rupture near faults, and marine waves resulted from seismic liquefaction and sliding are expected, there is not any published regulation. Therefore, in these conditions it is suggested to transform the building to a safer place. The purpose of seismic design of structures is achieving at least two purpose of three that noted previously, in other words in addition to preventing from life losses, it is expected to economic losses also minimized. The major difference that exists in these codes indicates the necessity of more careful studying of seismic behavior of different structures.

For designing of structures in seismically active zones the following statements should be considered:

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- With provision of enough rigidity and strength for the structure the lateral displacements could be controlled.
- With provision of enough deformability thus increasing the capability of energy absorption of the structure, the collapse of structure by the major earthquakes could be prevented.

According to above statements it is clear what the designer expect from every structure against different earthquakes. With this method, a proper design could be done in the desired place [12].

3-Nonlinear behavior of the structures

If real response of structures against major earthquakes is investigated, it can be understood that majority of structures have a nonlinear behavior. Nonlinear behavior also like linear behavior could be predicted. In other words, the horizontal zone of base shear vs. displacement curve could be increased significantly. Usually the base shear vs. displacement curve for a structure is as shown in figure 1.

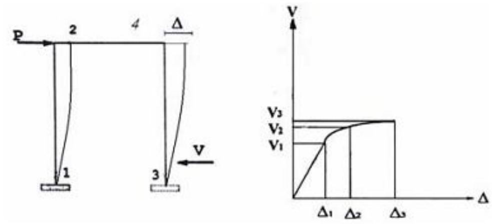

Fig. 1. Three-degree indeterminate frame subjected to an increasing load.

All the structures have a same behavior as shown in figure 1. In concrete structures, the nonlinear zone starts sooner than steel structures because the deformation of steel is essentially partial linear before yielding thus the steel structure behaves linearly at the beginning of loading.

The frame which is shown in figure1 is a three-degree indeterminate frame (have three degree redundancy). As noted in classic books for collapsing subject, in this frame at least four plastic hinges must form to occur mechanism if the partial buckling of the column does not prevail. For example the hinges can be considered in points 1 & 2 & 3 & 4 in figure 1[8].

In this structure if the load is applied increasingly, in other words it starts from low magnitudes and gradually increase (increasing loading), It is clear that the displacements is increased gradually and thus moments and shear forces also increase and finally first plastic hinge forms (for example in point no 1), but in this condition the structure is still stable and the load could be increased, and with increasing the applied load stresses in the structure reach the limit which the second plastic hinge also is formed (for example in point no 2). Although two plastic hinges are formed the structures could be laterally loaded again, then the load could be increased until the third plastic hinge is formed (for example in point no 3) and finally the forth in point no 4 and mechanism is formed. As noted previously the structure could be designed so that its plastic hinge could withstand significant rotations. If design engineer be able to do so, in other words the structure could withstand considerable deformations without collapsing, it can be expected that the horizontal zone of base shear vs. displacement curve (that is started with forming first plastic hinge and continue until occur mechanism) is increased [1]. In other words, with adopting special methods in the zone of hinges the base shear vs. displacement curve could be leaded from curve (b) to curve (a) in figure2.

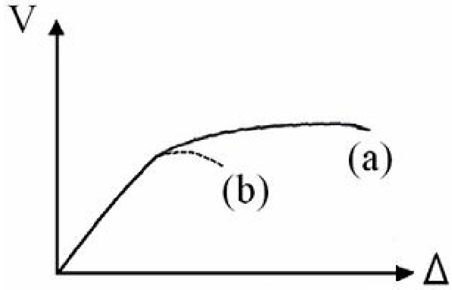

Fig. 2. Schematic curves of base shear vs. displacement for deformable and rigid structures.

The differences in curves (a) and (b) resulted from the modifications that are adopted in this structure with base shear-displacement curve (a). This structure is designed so that its first plastic hinges are not collapsed while forming subsequent plastic hinges. This point is the main principle of designing of structures.

4-Nonlinear static analysis method

Nonlinear time history analysis is the best method for structural analysis but there are principle problems in this method among them: Investigation of the kind of used accelerator, information about structural and nonstructural elements and theoretical problems about their capacity and many problems like this, So a simple method by the name of nonlinear static procedure is presented,such as the reference number 6 (Anil K.chopra & Rakesh K.Goel (2001)) and other references about relevant texts as is mentioned .

The nonlinear static analysis method for increasing load is introduced recently in new codes like FEMA and ATC. This method is a very attractive and useful method for studying the response of structures subjected to earthquake loads. Indeed, with this analysis method and innovative methods that are suggested in these codes, the response spectrum of the structure (that indicates the status of the structure under seismic spectrum) could be estimated. On this basis, the idea of designing of the structure based on its response is presented recently. This idea is attractive for many structural and earthquake engineers and it is predicted that in the future the classic design methods is replaced by this new designing method. According to development of engineering programs and capability of adopting of algorithms of these methods, the capability of performing nonlinear static analysis is equipped in programs like ETABS and SAP2000 [5].

With using nonlinear analysis method, the response spectrum of the structure under a special seismic spectrum and all of the final parameters like increasing factor of nonlinear displacements and behavior factor (R) could be calculated. Using nonlinear analysis other than code recommendations and specifications can be very useful in identifying the probable weaknesses of the structure. It means after final designing of the structure, the designer could find the locations of plastic hinges with using programs like ETABS and SAP2000 by using nonlinear static analysis, by doing so the designer could prevent from early collapse of these hinges when the structure is subjected to earthquake. The prerequisite of any nonlinear analysis is knowing the properties of the nonlinear hinges. These plastic hinges are defined in the points of elements where the internal forces may exceed the yield force. In nonlinear program SAP2000 analysis the path of introduced loading (for example earthquake loading) is applied in sequence steps and in every step the stiffness matrix is modified according to the deformed geometry. Moreover the internal forces of element in hinge locations are compared with the defined limit yield force of hinges. If the internal force did not reach to the yield stress, the load is increased partially but if the internal force is exceeded from yield force of the hinge the hinge stiffness and hence the structure stiffness is modified according to force-displacement curve and the load of the next level is applied. This loading continues until the mechanism occurs, or the structure reaches to displacement criterion that is defined by user [11].

4-1-Advantages of nonlinear static method

The below subjects could not be achieved from linear static and dynamic analyses but they could be estimated by using nonlinear static method:

- The force magnitudes in brittle elements like: axial force in columns, bracings, and hinges and shear forces in joints of beam and column and reinforced deep concrete beams.
- Estimate of deformation magnitudes in nonlinear elements.
- Determination of critical zones in the structure that its deformations are critical.
- Determination of discontinues points of strength in plan or height of the structure which results to nonlinear dynamic properties
- Estimate of mid-story deformations with considering discontinues strength for damage control
- Reviewing force path with considering all of the structural elements like joints, stiff nonstructural elements and foundation, and controlling of strength magnitudes [4], [10].

It must be noted that the last term is the main result of this analysis. In this method a model is built that all of its structural and nonstructural elements that are effective on force distribution are investigated in this model.

5 - Modeling and analysis

5 -1- Introduction to modeled frames

In this paper two four and eight-story buildings (that are common) are modeled. As we noted before these structures have concentric braced steel frames. For verification of our results with the reality, it is tried to use common sections for designing of this structure. The other point that is considered is the arrangement of sections; they are modified so that the structures have proper deformability. It is possible that in ordinary designing methods of structures, the structures could not show enough deformability and even don't reach to expected deformations and it yields in early stages. This may be because of high strength of the sections or weakness or incorrect arrangement of them [13].

5-2- The general properties of the structures

The studied frames are two four and eight story structures with concentric braced frames.

5-2-1-properties of the materials

Density = 8000kg/m^3
Young modulus = 2.039e10 kg/m^3
Shear modulus = 7.842e9 kg/m^3
Poisson ratio = 0.3
Yield strength of steel = 2530 kg/cm^2

5-2-2- dimensions and applied loads to all of the structures

The structure is a four-story building with three 5 meters spans in x direction and four 4.5 meters spans in y direction. Therefore the final height of it is 12.8 m and the area of it is 270 $m^{2.}$ A rigid diaphragm walls is assumed around the vertical axis (in the direction of height of the structure)

5-2-3-The applied loads for designing of structure

The dead load is assumed 700 Kg/m^2 with consideration of equivalent wall loads. The live load is assumed 200 Kg/m^2 and the peripheral wall load is 600 Kg/m with considering 30 percent opening. In addition the dead loads of columns and beams also considered in calculations [7]. Earthquake loads are calculated according to seismic codes of Iran (close similarity to UBC94).

$$V=CW \quad (1)$$

Where:
C=ABI/R=0.145, A=0.35, To=0.1, Ts=0.5 S=1.5, I=1, R=6, B= (1+S) =2.5,
T=0.05* H^3/4=0.338s

And W= total weight of building
C = Seismic factor
V = basic shear force
A = basically acceleration ratio of model
B = Reflection factor of building
I = Importance factor of building
R = Behavior factor
H= Height of building from basic level
To, Ts, S = dependent factors to the type of soil

Assumption: the zone is with seismic relative very high hazard
Assumption: soil type 2

The structure is an eight-story building with three 5 meters spans in x direction and four 4.5 meters spans in y direction. Therefore, the final height of it is 25.6 m and the area of it is 270 $m^{2.}$ A rigid diaphragm walls is assumed around the vertical axis (in the direction of height of the structure)

C=ABI/R=0.134, A=0.35, To=0.1, Ts=0.5 S=1.5, I=1, R=6, B= (1+S)* (Ts/T) ^2/3 =2.29
T=0.05* H^3/4 = 0.569s

Assumption: the zone is with seismic relative very high hazard
Assumption: soil type 2

6-ANALYSIS AND RESULT

At first two models (eight and four story structures) were analyzed and designed linearly and all of the sections were selected optimally. After performing this step the structures are analyzed nonlinearly. In all of analysis steps the resulted deformations for the structures have been compared with target deformation and the magnitude of deformation have been assessed with this standard. In the first step the four-stories showed a perfect undeformable behavior. It can be concluded from noticing figure 3 to 7 that the early mechanism of the structure is improper process of forming plastic hinges in bracings and adjacent columns [3]. These figures show that yielding of elements is not formed with a logical trend and the bracings of the lower stories are yielded earlier than higher stories and before the structure deforms significantly the mechanism is formed [9].

As shown in figure 3, yielding is started from bracings of the third story. The high stiffness of the fourth story could be one of the reasons of not forming plastic hinges in this story.

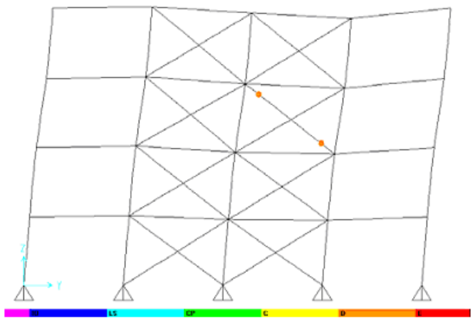

Fig. 3. Yielding of the bracing in the third story.

The figure 4 shows that the yielding is occurred in the next step in the bracings of the ground story.

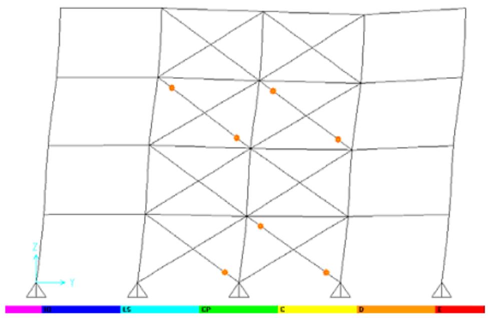

Fig. 4. Yielding of bracing in the ground story.

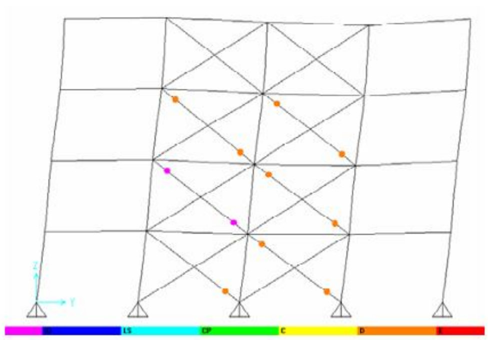

Fig. 5. Yielding of bracing in the second story.

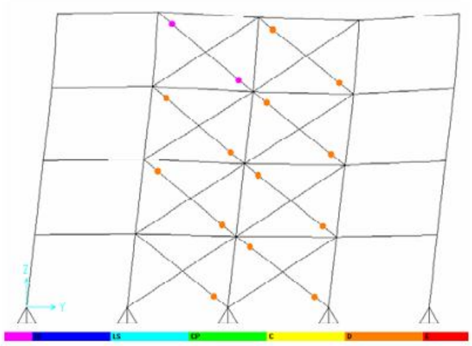

Fig. 6. Yielding of bracing in the forth story.

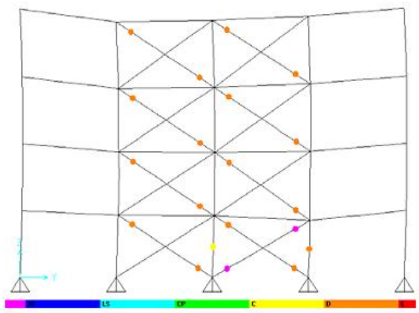

Fig. 7. Yielding of columns adjacent to bracings.

At the end of the process of forming mechanism, the columns of ground story which are conduced to bracings also yielded. This process is the main cause of instability of the structure.

As is shown in figure 8 at the first the structure did not show proper nonlinear behavior and after bearing small deformation, it will collapse. The modification of the structure is done in subsequent steps. This process is done according to the previous studies and trend of forming plastic hinges and using of the results of the previous step. For example in the first step the columns adjacent to bracings in ground story are reinforced [6].

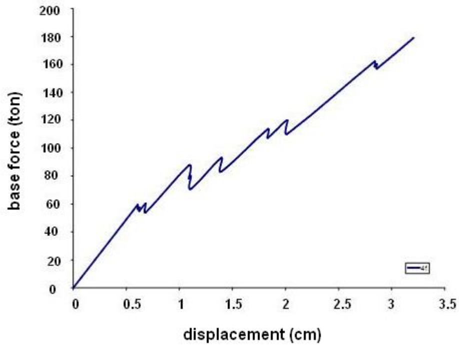

Fig. 8. Load-displacement curve of the four story structure.

As shown in figure 9 with reinforcing columns adjacent to bracings in ground story the inelastic behavior of the structure is improved up to some extent. In the following with modifying the structure and changing the sections in use the load-displacement curves become more reasonable.

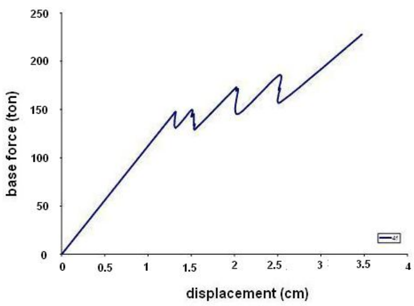

Fig. 9. Load-displacement curve of the four story model after first modification.

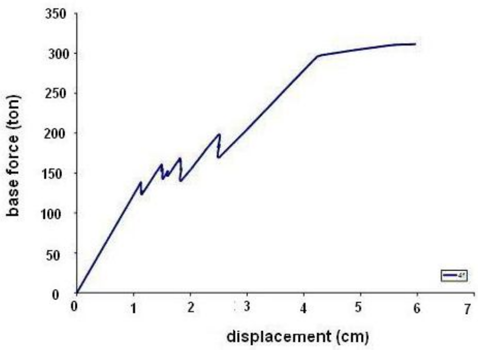

Fig. 10. Load-displacement curve of four story model after second modification.

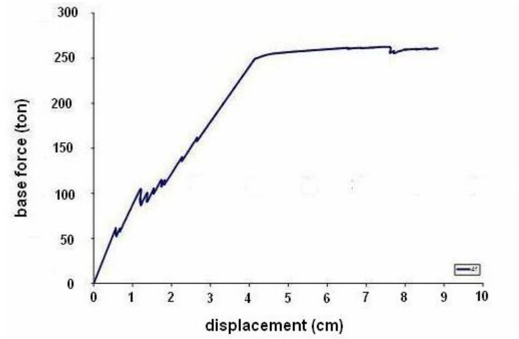

Fig. 11. The final load-displacement curve for four story structure.

For modifying of deformability process with looking carefully to the load-displacement curves and the mechanism and final deformations of the structure it can be noted that the columns adjacent to bracing play an important role in deformability of the structure. The process of improving the curves is performed with modifying of these columns. In all steps, the load-displacement curves in each step are the modifying guide in the next step [2].

The eight-story structure also is analyzed with the same precondition as the four-story structure. Again it could be seen that the structure wouldn't show proper nonlinear behavior and would not show significant deformations. With modification of the load-displacement curve it improves and it gains more proper shape.

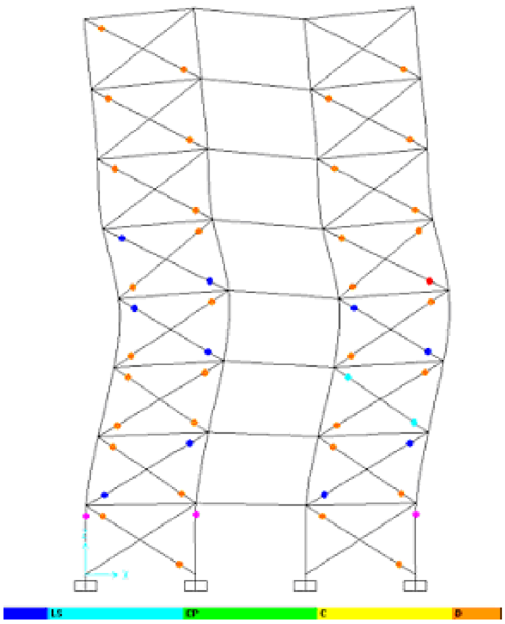

Fig. 12. Yielding of column adjacent to bracings and mechanism.

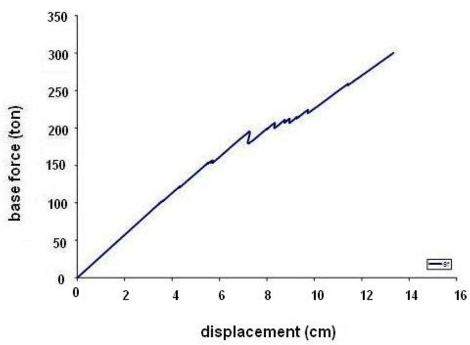

Fig. 13. Final load-displacement curve of the eight-story model.

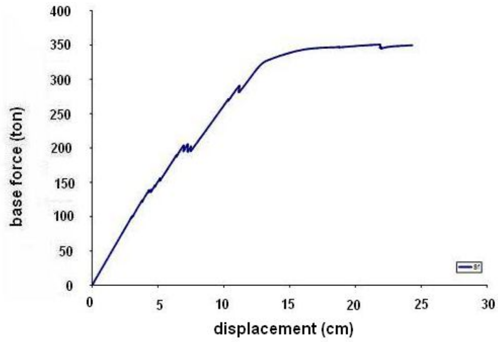

Fig. 14. Final modified load-displacement curve of the eight-story model.

At the end it can be noted that the modification process could be continued but at least it is expected that the structure could maintain its stability until reaching to target displacement. Also it is seen that after reducing the dimensions and weakening the sections the behavior will be improved. Thus proper arrangements of the elements have an important role in the deformability of the structures.

7- Conclusions

After performing the analyses and analyzing the obtained results for the investigated structures the following terms could be concluded:

- The increasing static nonlinear pushover analysis with showing the yield mechanism trend could help significantly to proper designing of a deformable structure. And this is very useful in the stabilization of the structures.
- Improper distribution of the stiffness in the structure resulting from inaccurate arrangements and sudden variations of the sections (weakness or high stiffness of the sections), will reduce the deformability of the structure.
- The structure behavior could be improved significantly with adopting nonlinear analysis. As was noted the nonlinear analysis would lead to changing the sections and modifying the stiffness of the structure hence improving the plastic hinge formation trend.
- In the steel structures with concentric braced frames not only the bracings but also the columns play an important role in the deformability of the structures.
- In the steel structures with concentric braced frames, the high stiffness in the structure, especially in the points of lower end of columns, have weakness and totally wouldn't show significant deformations. This subject must be considered in designing.

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