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Seismic Behavior Evaluation of Semi-Rigid Steel Frames with Knee Bracing by Modal Pushover Analysis (MPA)

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***Abstract*—**Nowadays use of a new structural bracing system called 'Knee Bracing System' have taken the specialists attention too much. On the other hand nonlinear static analysis procedures in estimate structures performance in earthquake time have taken attention too much. One of these procedure is modal pushover analysis (MPA) procedure. The accuracy of MPA procedure for simple steel moment resisting frame has been verified and considered in Chintanapakdee and Chopra's article in 2003. Since the accuracy of MPA procedure has not verified for semi-rigid steel frames with knee bracing, we are going to get through with this matter in this study. For this purpose, the selected structures are four frames with different heights, 5 to 20 stories, will be designed according to AISC criteria. Then MPA procedure is used for the same frames with different rigidity percentiles of connections. The results of seismic responses are compared with dynamic nonlinear response history analysis as exact procedure and accuracy of MPA procedure is evaluated. It seems that MPA procedure accuracy will come down by reduction of the rigidity percentiles of semi-rigid connections.

***Keywords*—**Knee Bracing, Modal Pushover Analysis, Seismic Behavior, Semi-Rigid Connections.

I. Introduction

MOST of steel frames are modeled fully rigid which beam to column connection is enough rigid and angel between beam and column kept fixed during frame deformation, or ideally pinned which beam to column connection is without rigidity and can rotate under the effect of vertical loads. Actually, the pinned ones have some rigidity moment and the rigid ones do not functions completely as rigid. These connections which have different rigidity percentiles can be considered as semi-rigid connections**.** In addition to, reaching to an economical and resistant structure needs to a suitable compound of strength, stiffness and ductility so moment resisting frame and centric bracing frame cannot responsible for stiffness and ductility at the same time, because moment resisting frame shows a good ductility by yielding the beam flexural member but it has low stiffness whereas centric bracing frame has more stiffness but it's ductility is reduced because of diagonal brace buckling. For solving this problem Roeder and Popov [1] have proposed an eccentric bracing frame (EBF) which has suitable performance but it has some defects. So knee bracing frame has proposed by a designer engineer Aristazabel Ochoa [2]. In this framing system, a special form of diagonal brace connected to a knee element instead of beam-column joint.

The diagonal element provides lateral stiffness during moderate earthquakes and knee element is designed to behave like a structural fuse such that by sustaining controlled inelastic deformations and dissipating seismic energy, other members and connections would remain elastic.

Some excellences of this system are ductility, energy dispose through the knee element and simple changeability of the knee element. In the most present buildings codes, the structural design methods are depend on strength factor whereas research on the in recent earthquakes indicated that strength cannot be a suitable factor only. In according to functional criterions, new building codes use behavior factor instead of strength for structural design. Nonlinear static analysis methods have special rules in performance design methods.

There reason is simplicity in procedure, saving the time, expenditure and acceptable estimate of them in seismic demands in comparison with nonlinear dynamic analysis procedure**.** The main problem of simple nonlinear static analysis method (pushover method) is that it does not consider the effect of higher modes in estimating structure responses which is solved by modal pushover analysis (MPA) method. Among the simplified nonlinear procedures in order to including in the rising generation of the building codes, modal pushover analysis (MPA) easily simulates the nonlinear behavior of structure and by using a lateral load pattern according to mass, will present a very good approximate of nonlinear dynamic analysis. In this research, by modeling of some building frames with compound of above mentioned systems (semi-rigid frames and knee bracing system), seismic responses of frames are obtained throw MPA method [3].

II. Semi-Rigid Connections

The necessary parameters for describe the behavior of the semi-rigid connection element are initial stiffness, secondary stiffness (after yielding) and amount of yielding moment which are acquired by lab data and analytical investigations on semi-rigid connection. We use "beam line theory" for determination of connection stiffness (see fig. 1).

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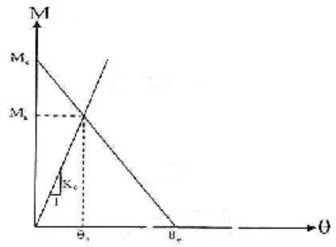


Fig. 1 Beam line for beams with rigid and semi-rigid supports under distributed load

M_e: Moment of beam with 100% end rigidity
M_a: Moment of beam with R% end rigidity
θ_e: Rotate of beam with 100% end rigidity
θ_a: Rotate of beam with R% end rigidity
K_θ: Connection stiffness

The amounts of stiffness for 3 types of rigidity (90%, 75% and 50%) are obtained from (1):

$$K_\theta = \frac{2REI}{(100 - R)L} \quad (1)$$

Which E is module of elasticity of beam, I is moment of inertia of beam, L is length of beam and R is connection rigidity percentage. Whenever moment-rotate curve of connection interrupts beam line, this point indicates the moment of connection.

Under investigation software accepts the connection behavior as bilinear, so we must estimate the connection nonlinear behavior as two straight oblique lines. First line's slope indicated the initial stiffness of connection and the second line's slope indicates after yielding stiffness of the semi-rigid connection which is acquired by lab investigations about 10% to 15% of connection initial stiffness. We consider 10% for that in software models. For strength of the first phase (My), we suppose that the strength of connection is smaller than beam strength, so we consider 75% of the yielding moment of the beam for that which shows bolted semi-rigid connection behavior.

III. Ground Motions

Seismic excitation is defined as a set of 15 records of earthquake which listed in table 1. For taking average, it is necessary that selective records be related to one area. For this reason all records are selected from California earthquakes with large severity (M=6.5-6.9 Richter) and minor radius (R=13-30 Km) which are registered on hard soil (site NEHRP class D). For unifying the responses, the records are not near fault records.

TABLE I
Earthquake Records Specifications

Record Number	Earthquake	M	Station	R(km)	PGA (cm/s2)	PGV (cm/s)	PGD (cm)
1	Imperial Valley 1979	6.5	Chihuahua	[illegible]	249	[illegible]	[illegible]
2	Imperial Valley 1979	6.5	Compuertas	[illegible]	[illegible]	[illegible]	[illegible]
3	Imperial Valley 1979	6.5	El Centro Array #13	[illegible]	[illegible]	[illegible]	[illegible]
4	Imperial Valley 1979	6.5	Parachute Test Site	[illegible]	[illegible]	[illegible]	[illegible]
5	Loma Prieta 1989	6.9	Gilroy Array #3	[illegible]	[illegible]	[illegible]	[illegible]
6	Loma Prieta 1989	6.9	Gilroy Array #4	[illegible]	[illegible]	[illegible]	[illegible]
7	Loma Prieta 1989	6.9	Hollister City Hall	[illegible]	[illegible]	[illegible]	[illegible]
8	Loma Prieta 1989	6.9	Hollister Diff Array	[illegible]	[illegible]	[illegible]	[illegible]
9	Loma Prieta 1989	6.9	Saratoga - W Valley Coll	[illegible]	[illegible]	[illegible]	[illegible]
10	Northridge 1994	6.7	Canoga Park - Topanga Canyon	[illegible]	[illegible]	[illegible]	[illegible]
11	Northridge 1994	6.7	Canyon Country - W Lost Cany	[illegible]	[illegible]	[illegible]	[illegible]
12	Northridge 1994	6.7	Northridge - Saticoy St	[illegible]	[illegible]	[illegible]	[illegible]
13	Superstition Hills 1987	6.7	El Centro Imp Co Cent	[illegible]	[illegible]	[illegible]	[illegible]
14	Superstition Hills 1987	6.7	Westmorland Fire Station	[illegible]	[illegible]	[illegible]	[illegible]
15	Superstition Hills 1987	6.7	Wildlife Liquef Array	[illegible]	[illegible]	[illegible]	[illegible]

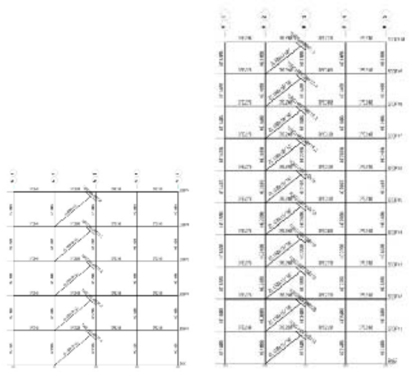
IV. Loading

We consider some hypothesis in loading as follows:

1. We suppose that stories floors are rigid.
2. Floors dead load is 600 Kg/m^2 and floors live load is 200 Kg/m^2.
3. Every stories mass is computed from dead load + 20% of live load and is divided equally between story nodes.
4. Under investigation frames are middle frame with 4m loading span.
5. Lateral resistant system of frames is dual system.

V. Analysis and Design of Frames

After loading, the frames with 100% rigidity of connections and considering of P-Δ effect, were analyzed and then were designed on the basis of AISC [4].



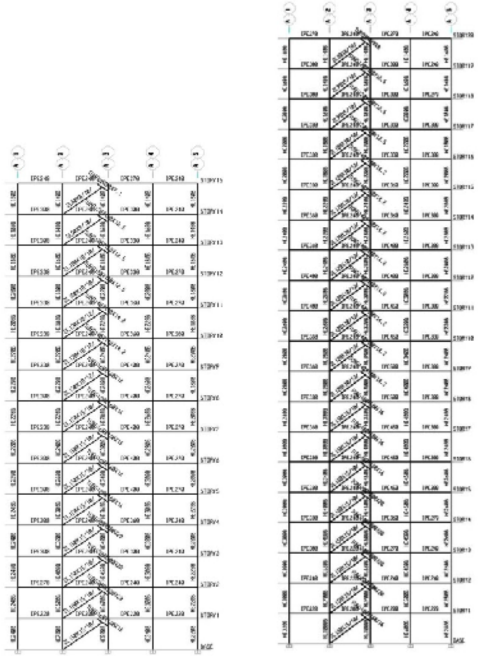


Fig. 2 Under consideration frames

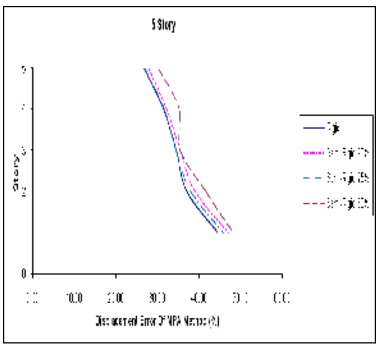
VI. METHOD IMPLEMENTATION

In view of the fact that MPA method is considered for a large sector of buildings and ground motions, so the result of a single accelerograph can not be enough and it is necessary to have several accelerographs for statistical consideration of MPA method responses. Furthermore, seismic demands average of MPA method and nonlinear response history analysis (NL-RHA) method are considered and compared with each other and the statistical results of MPA method are adduced and analyzed (fig 3 to 7).

The responses parameters which are acquired from analysis and compared are as follows:

- Maximum displacement of story as percentage of frame height.
- Percentage of story drift ratio.

Second parameter is more suitable criterion in evaluation of structure damage.



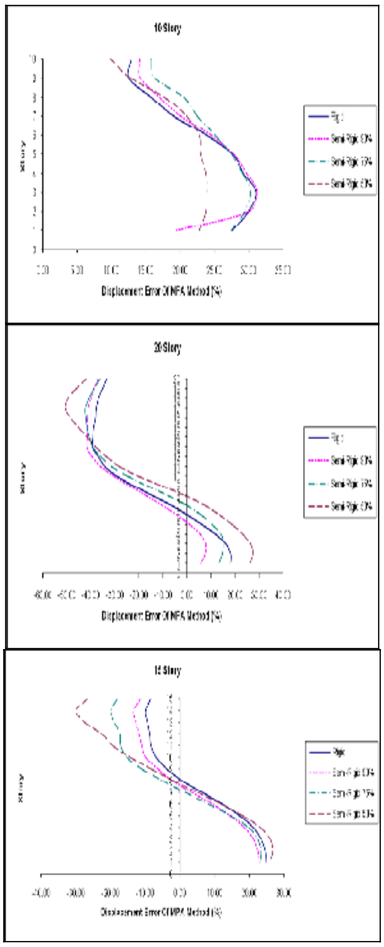
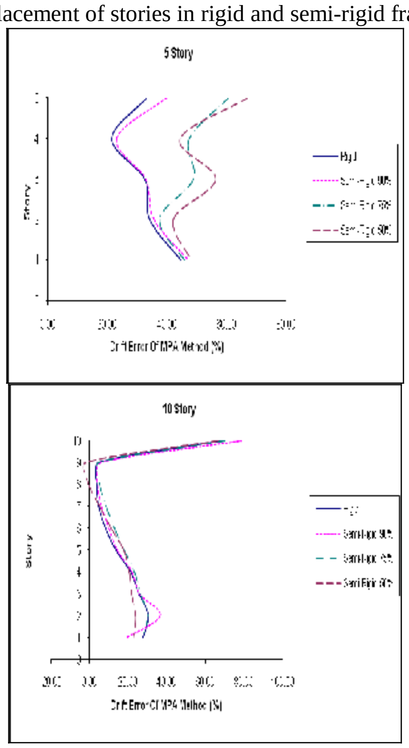


Fig. 3 Error of MPA method in estimation of maximum displacement of stories in rigid and semi-rigid frames



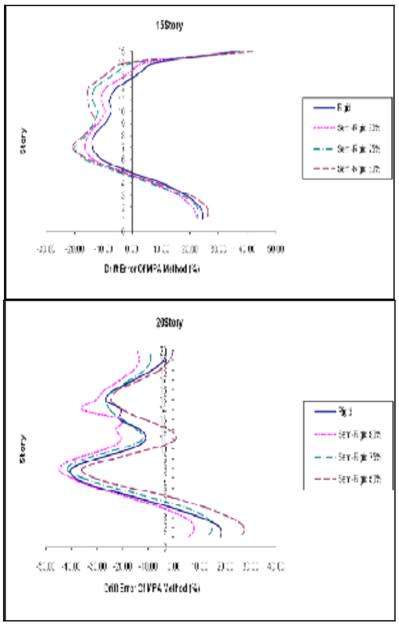
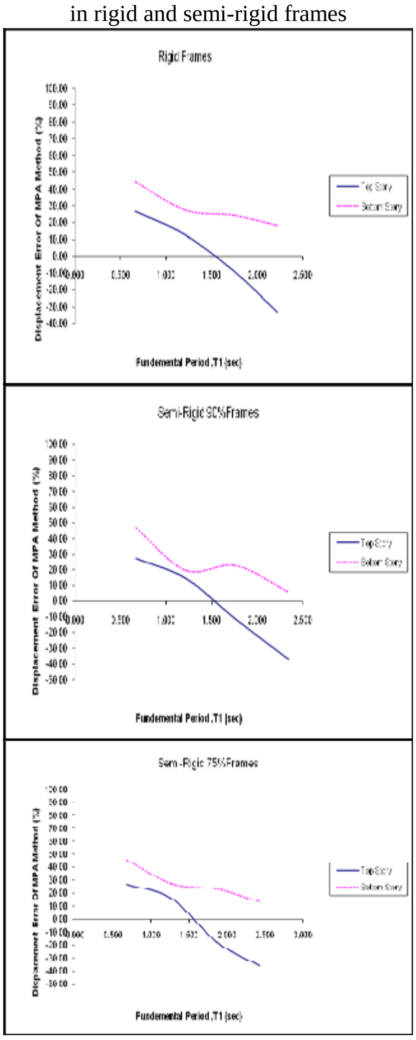


Fig. 4 Error of MPA method in estimation of maximum story drift in rigid and semi-rigid frames



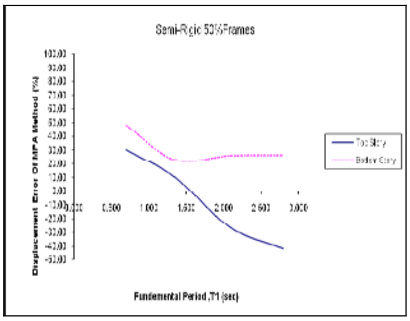


Fig. 5 Error of MPA method in estimation of maximum displacement of stories for top and bottom story versus the fundamental period of rigid and semi-rigid frames

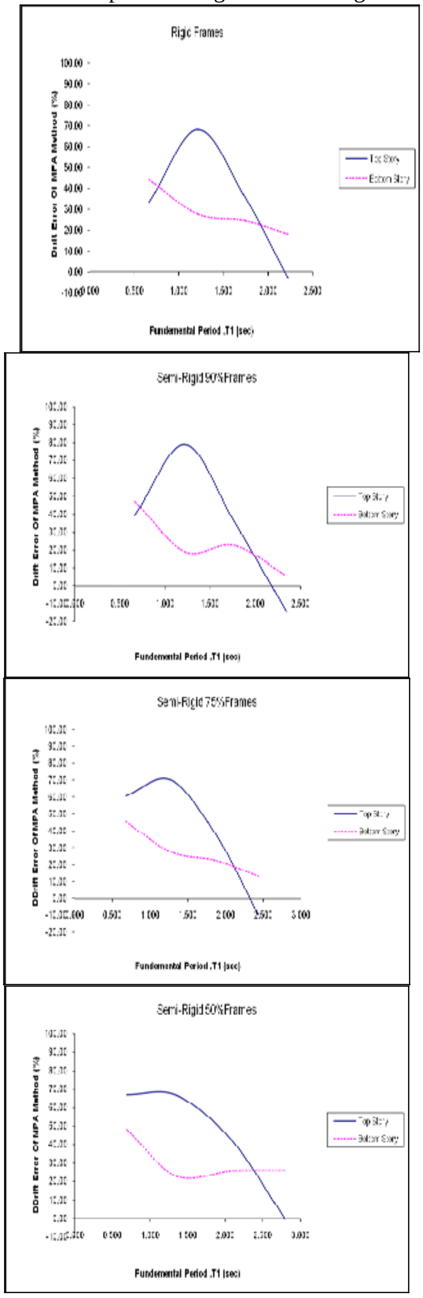


Fig. 6 Error of MPA method in estimation of maximum story drift ratio for top and bottom story versus the fundamental period of rigid and semi-rigid frames

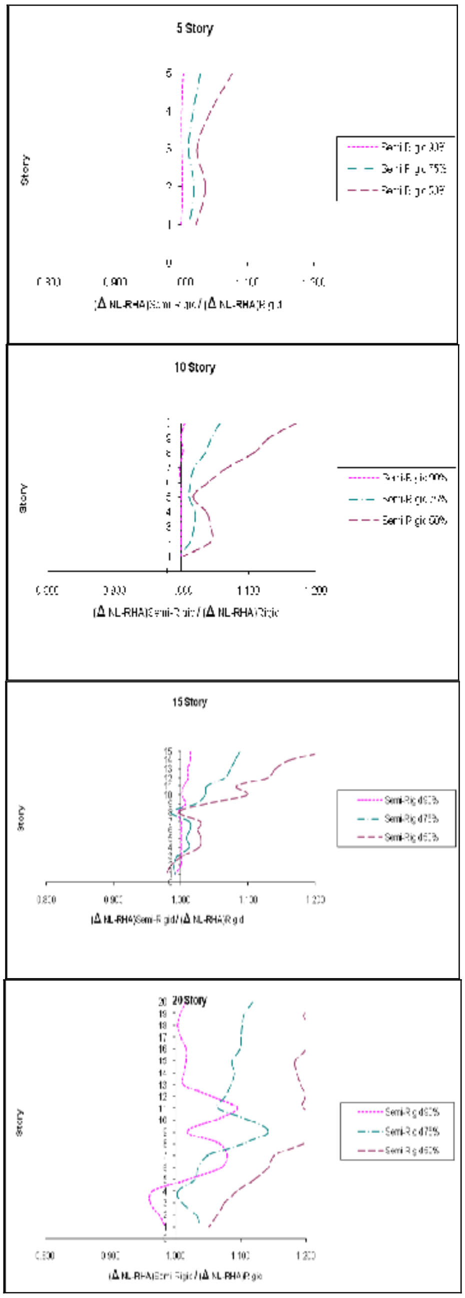


Fig. 7 ratio of story drift ratio of semi-rigid frames to rigid frames with using of NL-RHA method

VII. Results

In this article, evaluation of precision of MPA method is accomplished trough consideration of seismic responses of 16 rigid and semi-rigid steel frames with knee bracing, under the effect of 15 earthquake records and acquired results average is compared with NL-RHA method as an exact method. Under consideration responses consist of maximum displacement of stories as a percentage of story's height and maximum story drift ratio. The acquired results are as follows:

1- Base shear of frames becomes lesser with reduction of connection rigidity of frames.
2- Frames ductility increases with reduction of connection rigidity of frames.
3- In according to base shear reduction and ductility enhancement of semi-rigid steel frames with knee bracing in comparison with rigid frames, we can say that using of semi-rigid connection in those frames cause better nonlinear behavior by control of displacement of frame in allowable range.
4- Fundamental period of frames will increase with reduction of connection rigidity and increase of frame's height.
5- The first plastic hinges is made in knee element after entrance the frames in nonlinear zone and these members act as a structural fuse and protect beams and columns from damage. In view of the fact that these members are simply changeable, using of this lateral load bearing system is economically beneficial.
6- In short frames with 5 stories, using of MPA method with consideration of one mode makes more precise results. Precision of these results for story drift, which have important role in structure damage, is more than maximum displacement of stories.
7- In 10 stories frames, using of MPA method with consideration of one mode, makes more precise results for maximum displacement of story and with consideration of two modes, makes more precise results for maximum story drift.
8- In intermediate frames with 15 stories, using of MPA method with consideration of two modes makes more precise results. Precision of these results for story drift in upper stories, which are critical, is more than maximum displacement of stories.
9- In tall frames with 20 stories, using of MPA method with consideration of three modes makes more precise results. Precision of these results for story drift, which have important role in structure damage, is more than maximum displacement of stories.
10- With increase of frame's height, importance of consideration of upper modes in MPA method is increased.
11- MPA method indicates short frame's responses with high approximation, but with increase of frame's height, this method tends to indicate the responses with low approximation.
12- In short and intermediate frames, and also in upper stories of tall frames which have the most responses, precision of MPA method will reduce with reduction of connection rigidity.
13- With increase of fundamental period of different frames with same rigidity, the precision of MPA method in indication of bottom story responses is

almost fixed and these responses are computed with high approximation.

14- With increase of fundamental period of different frames with same rigidity, the precision of MPA method in indication of top story responses is not fixed and these responses are going from high approximation to low. The form of this reduction of approximation for story drift is like a constant linear reduction form with reduction of connection rigidity.

15- Nonlinear response history analysis (NL-RHA) method shows that whenever percentage of connection rigidity has more reduction, usually increase maximum displacement of stories and story drift. This increase in upper stories is more noticeable than lower stories.

16- The seismic behavior of semi-rigid frames with 90% rigidity of connections is nearer to seismic behavior of rigid frames. The seismic behavior of semi-rigid frames with 75% and 50% rigidity of connections, have an additional effect on responses rather than rigid frames.

17- The results of this research is acquired for two dimensional rigid and semi-rigid steel frames with knee bracing which are designed on the basis of AISC code, and may be not correct for other frames with different conditions.

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