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Evaluation of drift distribution in performance-based retrofitting of RC frames

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ABSTRACT: As an experienced retrofit scheme, concentric structural brace elements are installed in reinforced concrete (RC) frames to upgrade original existing buildings. In the current research installed brace elements are designed based on force and satisfying seismic performance levels of structural elements under lateral loading. The drift distributions of stories for both forces-based design (FBD) and performance-based design (PBD) of steel braces are evaluated in retrofitted RC frames. On the basis of pushover analysis damage distributions and corresponding performance levels of formed plastic hinges are investigated as well. Results show, performance base design causes different drift distributions pattern from that of force base design. It is recognized that designing brace elements on the base of force concentrates structural damages, while performance base design spreads damages and therefore prepares higher seismic performance levels and satisfies retrofit goals.

1 INTRODUCTION

Installing steel brace elements to the reinforced concrete (RC) frames is a feasible effective approach that provides retrofit purposes. Several researchers conducted experimentally and analytically investigations to study seismic behavior of rehabilitated RC frames. A. Ghobarah and H. Abou Elfath (2001) retrofitted a nonlinear three stories building using concentric an eccentric inverted-V steel brace elements. T.EL-Amoury and A. Ghobarah modeled nine and eighteen stories RC frames analytically to study seismic behavior under various scaled motions. M.R. Maheri, R. Kousari and M. Razazan developed experimental testes on the ductile RC frames with X-brace elements. Seismic evaluation of RC frames with inverted V-brace elements, formation of plastic hinges and their local and global performance levels shows a considerable improvement in rehabilitated RC frames. Generally the seismic rehabilitation is achieved to upgrade the original performance to satisfy higher seismic demands of current code. Over the last couple of decades a lot of endeavors put on developing a new method of analysis and explicit designing regarding to various level of hazard and multiple criteria for levels of local and global performance. Now after establishing wide research on conventional method and using advances of earthquake engineering; retrofit technique may be selected in accordance with required performance. However the codes do not clearly prepare a guideline to design braces elements of RC frames based on performance.

The first attempt was standardized the performance-based design approaches by Federal Emergency Management Agency (FEMA) that sponsored the development of national guidelines for the seismic retrofit of buildings; ATC-33 project (1992). Displacement-based design (DBD) as a simplified approach of performance based-design (PBD) was proposed initially for bridges (Kowalsky et al. 1995). These two approaches have been used interchangeably, because performance objects can be related to the level of damages to the structure which can be expressed in term of displacement or drift. The approach was adopted by Structures Engineering Association of California (SEAOC) to design new buildings (2000) on the basis of pushover analysis. In current paper brace elements of RC frames design based on strength and performance level. The static nonlinear pushover analysis was performed because it may provide much of the needed information. According to pushover analysis method predetermined load applied and gradually increased until the displacement of roof reaches to target displacement. The drift distributions of retrofitted frames were evaluated. Formation of plastic hinges and their performance levels were investigated.

2 MODELS GEOMETRY AND MECHANICAL PROPERTIES

Models selected for analytical investigation consist of four reinforced concrete frames with three, five, seven and ten stories. The frames have three spans of 4.0 m and the same height of 3.1 m. Frames are symmetric and tensional effects are minimal. Frames were considered being moment resisting with intermediate ductility. Dimensions of beams, columns and details of reinforcement calculate to provide enough capability for frames to withstand seismic loads estimated by previous Iranian code. Due to that square column sections from 300 mm to 600 mm were used and, with reinforced ratio not exceeding about 2%. Beams sections varied from 300 × 300 to 450 × 600 (mm^2). Beams and columns cross-sections keep the same in every two stories. It reassures that strong-column and week-beam principal is reserved. Concrete comprehensive of 21 MPa and steel yield strength of 350 MPa were used for materials. The initial elastic module for concrete material is 80 GPa and for steel material is 200 GPa.

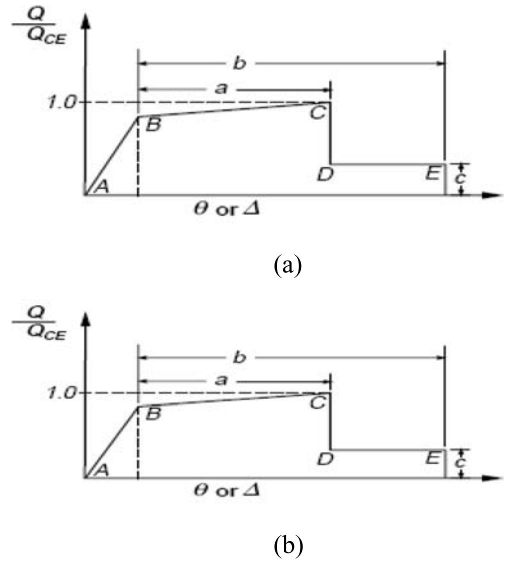

Figure 1. Generalized load-deformation relationship.

3 RETROFIT SCHEME

Many approaches and techniques have been studied and practiced for recent 20 years to upgrade and improve seismic performance of existing structures. The aims of rehabilitation are: (a) to recover original structure performance (b) to upgrade original performance; and (c) to reduce seismic response; so as to building earthquake vulnerability. As an effective scheme concentric inverted V-brace elements are added to existing RC frames to upgrade original performance of them. Structural steel brace elements install using three connections. Plates and bolds connects brace element to column and beam at one end at their joint and fixed it to the middle of mid-span beam at the other end. Based on conventional approach new added structural elements reduce large response displacement, so higher performance for retrofitted RC frames are expected.

4 NONLINEAR DEFINITIONS AND MODELING

Structural elements were modeled using elastic elements with two nonlinear hinges at their ends. In fact hinges represent material nonlinearity during gradually loading. Due to that beams modeled using linear elastic element with two point moment hinges. Yield moment introduce as a bending moment. Nonlinear behavior of plastic hinges defined according to generalized load-deformation relation diagram; Figure 1a and 1b. In current research parameters of nonlinear modeling (a, b, c, IO, CP, LS) extracted from tables which was prepared by FEMA273. Introduced parameters obtain based on geometry, concrete properties, corresponding transitive and longitude steel ratio. In other words bending and shear characteristics of hinges for the beams are defined according to the parameters in Equations 1 and 2.

$$3.77\frac{V}{b_w d\sqrt{f_c}} \tag{1}$$

$$\frac{\rho - \rho'}{\rho_{bal}} \tag{2}$$

For columns axial force-bending moment curve for plastic hinges were defined and assign to linear elastic columns. The same procedure conducted for beam plastic hinges, was used to find parameters of nonlinear modeling for column plastic hinges using computer macro. Corresponding reinforcement in the column are calculated using Equations 1 and 3.

$$\frac{P}{A_g f_c} \tag{3}$$

Load-deformation relation that represents nonlinear behavior of brace elements in tension and compression specified for each element. Parameters of nonlinear modeling or properties of brace elements hinges depend on yield stress and buckling limits in compression. Performance levels of hinges were extracted from tables which are recommended in chapter 5 of FEMA273.

5 DESIGN OF BRACE ELEMENT

In current research two different methods were carried out to design brace elements for each story. First traditional method is based on force. According to force-based design (FBD) philosophy the design criteria are defined by limits on stress from prescribe lateral loading. As second method, advanced methodology that is based on performance based-design set up for designing of brace elements. PBD procedure proposed a more general design philosophy regarding to multiple design criteria expressed in term of stated performance objects when the structure subjected to level of seismic hazard.

5.1 *Force-based design*

RC frames were braced using various tube sections, and increased lateral load were applied. Seismic loads were calculated according to modified Iranian Seismic Code. Linear dynamic analysis (LDA) performed and the amount of brace forces calculated. Brace elements were design for tension and compression according to Iranian steel structures.

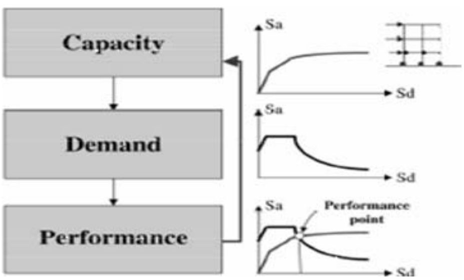

Figure 2. Performance base design procedure.

5.2 *Performance-based design*

Second upgraded method for designing braces is based on performance objects which expressed acceptable level of damage. According to performance based-design concept the aim is providing one of categorized performance level, such as immediate occupancy (IO), collapse prevention (CP) and life safety (LS). To achieve the aims, nonlinear static analysis (NSA) was performed to determine (1) capacity (2) demand (3) performance.

The capacity spectrums were obtained via pushover analysis. To achieve demand spectrum we used standard spectrum which was reduced due to 5% damping. According to definition the interaction of obtained spectrums determines performance point. Responses of building can be estimated based on assessing performance and hazard levels at target displacement. The responses can be checked against acceptability limits on either global system levels in term of stability and interstory drift or local element performance levels such as the element strength and sectional plastic rotation. In current investigation the brace elements design on the base of local element performance level observation at target displacement is developed. According to definition, target displacement is maximum

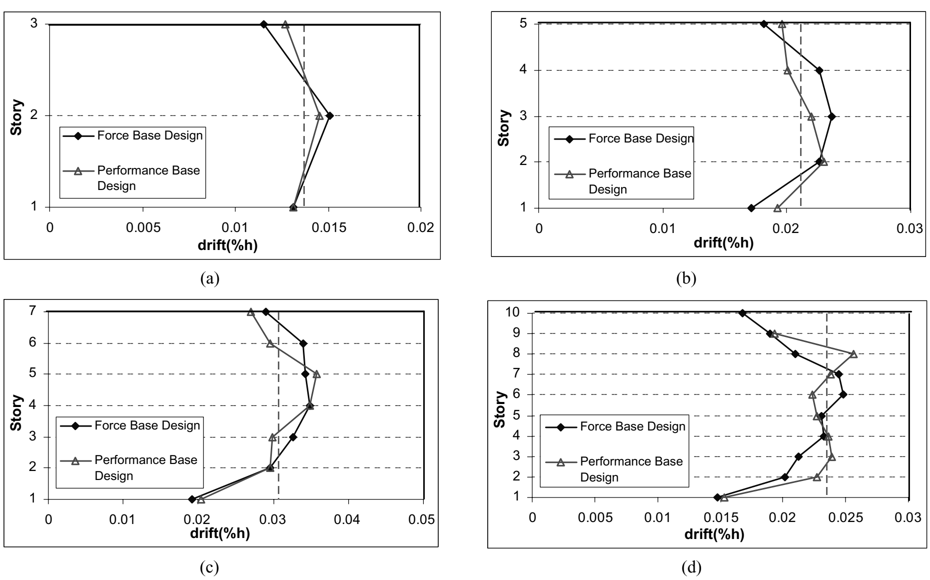

Figure 3. Drift distribution of braced RC concrete frames (a) Three stories, (b) Five stories, (c) Seven stories, (d) Ten stories.

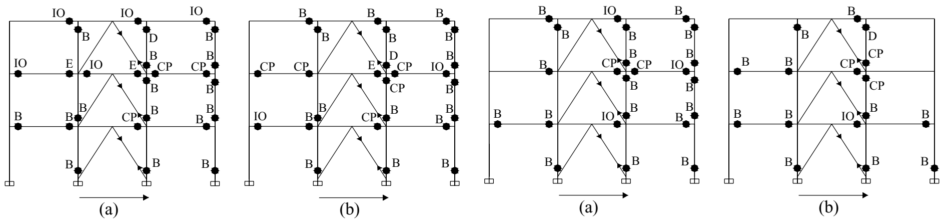

Figure 4. Formation of plastic hinges and local performance levels of structural elements (a) push1 (b) push2—Three Stories.

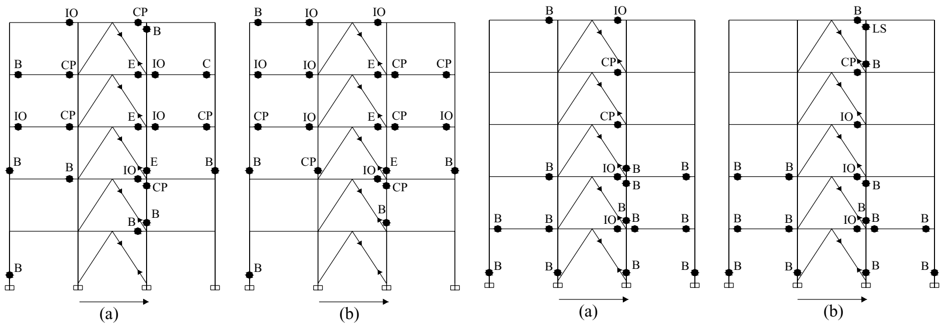

Figure 5. Formation of plastic hinges and local performance levels of structural elements (a) push1 (b) push2—Five Stories.

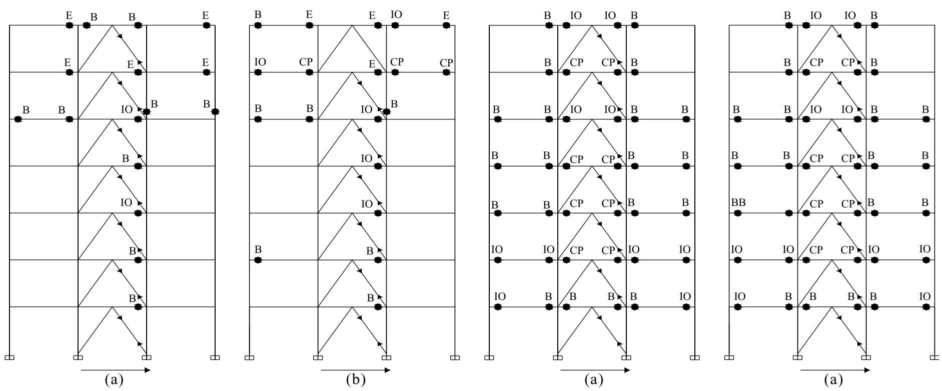

Figure 6. Formation of plastic hinges and local performance levels of structural elements (a) push1 (b) push2—Seven Stories.

probable displacement that building may experience during special earthquake. This drift is useful for engineers for the purpose of evaluation or retrofitting. Introduced displacement is estimated by Equation 4 due to the selected performance level. In this equation which is recommended by FEMA.

$$\delta_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2} g \tag{4}$$

parameters of nonlinear analyzing are C_0 modification factor to relate spectral displacement and likely building roof displacement, C_1 modification factor for maximum inelastic displacements, C_2 modification factor to represent the effect of hysteretic shape and C_3 coefficient factor for post-yield stiffness. Braced RC frames pushed to target displacement to evaluate formed plastic hinges performance. The drift of each frame obtain using PBS approach were compared with force base design approach.

6 COMPARISON OF DRIFT DISTRIBUTIONS

Figure 3 shows interstory drift distribution of 3-story retrofitted frame carrying out both force based-design and performance based-design approach. Comparison of drift distribution of three story frame reveals that RC frame retrofitted setting up performance base design method predict smaller drift for second floor than force base design method. It means performance based-design maintain brace elements with bigger dimensions for second floor. However this approach allows third floor has bigger drift. It can be recognized that PBD method estimate an over strength for third floor elements. Due to that PBD procedure achieves smaller dimension than FBD procedure for third floor braces used section. Figures 1, 2 and 3 illustrate inter-story drift distribution of five, seven and 10-story case study retrofitted based on two introduced design approaches. It is pointing out all three of them which are retrofitted using PBD method predict greater story drift for lower floors in compare with FBD approach. But as observed, frames retrofitted performing conventional approach base design show smaller drift for higher floors. An interesting point is that the values of calculated story drift based on PBD and FBD approaches coincide almost at 2/5 height of frames. As described before it can be obviously seen that the value of last story drift for PBD base retrofitting is smaller than one for FBD base retrofitting. It indicates an over strength presented in term of story drift.

7 EVALUATION OF EFFECT OF DESIGN APPROACHES ON DAMAGE

To evaluate the seismic capacity of retrofitted RC frames with more accurate and to obtain a precise understanding of differences in results of two applied design approaches, a complete set of nonlinear static (pushover) analysis were carried out. To achieve the aims, two types of gravity load which are restricted to $1.1(Q_D + Q_L)$ and $0.9(Q_D + Q_L)(Q_D)$; dead load and Q_L; live load), are pushed primarily according to FEMA273 recommendation. Then lateral load is gradually applied to achieve the target displacement. Consequently two types of nonlinear analysis could be defined such that for each of them lateral load follows one of defined gravity loads. Retrofitted RC frames using both performance based-design and force based-design were evaluated in term of formation of plastic hinges and their prepared local performance levels at target displacement. Figure 7 shows formation of plastic hinges at target displacement for frames retrofitted based on performance. As it is expected, almost all of formed plastic hinges remain in collapse prevention level. Figure 8 presents formation of plastic hinges in retrofitted frame based on force while subjected to lateral load. Comparison of them states FBD procedure concentrates damages on second floor structural elements. In other words columns damaged at target drift. Also chord plastic rotation of formed hinges exceeds CP level. However PBD distributes the damages along the height of frame. Seismic performance of rehabilitated five, seven, and ten RC frames are evaluated by conducting the same nonlinear analyzing procedure. Chord rotation in these RC frames retrofitted based design ranged from B to CP level while undergoing lateral loading. RC frames retrofitted using force based-design approaches could not provide expected seismic performance. Consequently many structural elements are significantly damaged. Formed plastic hinges with grater plastic rotation occurred in third floor column which is coded by D states a considerable concentrated damage in columns of retrofitted RC frames based on FBD approach. It is worth noting that reduction in brace area based on PBD procedure lead to an obvious difference in formation of plastic hinges and prevent

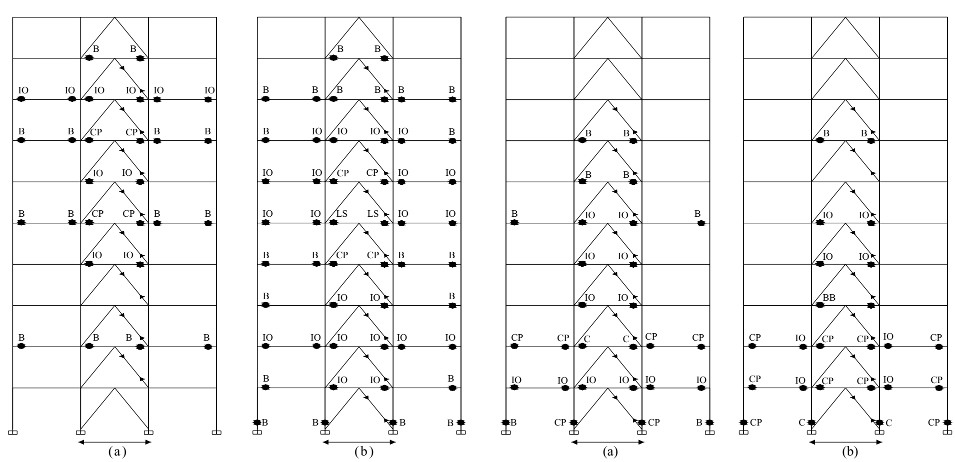

Figure 7. Formation of plastic hinges and local performance levels of structural elements (a) push1 (b) push2—Ten Stories.

from damages concentration. Due to that higher performance levels are achieved. Analyzing of seven and ten story RC frames with steel brace elements are clear testimony that proves inabilities of force base design retrofitting approach.

8 CONCLUSIONS

Comparing drift distributions for both applied retrofitting and applied retrofitting approach states results of PBD method more tend to a straight line pattern than FBD method. It can be distinguished PBD approach proposed for achieving higher seismic assessment; cross sectional areas of brace elements should distribute across the height of frame in manner of uniform drift distributions for interstory. Presented plastic hinges and consequently corresponding local performance levels of structural elements PBD approach prevent damages concentration due to miner plastic deformations. As a novel note, FBD method with strength limits and restrictions do not have enough ability to distribute braces optimal in other to use all seismic capability of week existing buildings as a retrofitting goal. However PBD procedure is more effective for retrofitting aims.

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