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## Research Article

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# Structural Member Sizes for Displacement-Based Design of Reinforced Concrete Frame Buildings

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**Abstract:** Unified Performance-Based Design (UPBD) method attempts to optimize the structural member sizes of RCC frame buildings for specific performance objectives, reducing the design iterative efforts and enhancing efficiency. Originally, UPBD was basically validated for certain material grades (M30 concrete and Fe415 rebar steel) and design parameters. In this study UPBD is tested for RCC framed buildings of; 2, 4, 6, and 8 stories; different design Interstorey Drift Ratios (IDR) - 1%, 2%, 3%; M20 Concrete and steel grades of Fe-415 and Fe-500. EC-8 design displacement spectrum at 0.45g seismicity level and type B soil condition is considered. The seismic performance of the structures is checked using Non-Linear Time History Analysis (NLTHA) based on the Spectrum-Compatible Ground Motion (SCGM). It is found that the structures achieved the desired performance levels and IDR with very small exceedance beyond the target IDR by 0.4% in few cases. The ductile failure modes are properly maintained. The resulting beam plastic hinge patterns are also in good terms with the existing equation. This study confirms that UPBD is a practical and effective tool for designing earthquake resistant RCC frame buildings within the considered scopes.

**Keywords:** Member Sizes, Reinforced concrete, Time history analysis, Inter-storey drift ratio, Plastic hinge rotation.

## 1. Introduction

Seismic design in building engineering involves designing structures that can withstand earthquake forces, ensuring safety and functionality after an earthquake. This requires strategic reinforcement, adherence to seismic codes, and knowledge of how buildings behave under dynamic forces. Traditional seismic design methods are typically based on Force-Based Design (FBD) principles. Force-based codal method of design focuses on determining the design forces which represents the most expected earthquake induced forces on the structure. The design base shear is computed based on perceive seismic hazard level and probable reduction in demand due to nonlinear hysteresis effect. However, since it is widely understood that damage correlates

more closely with displacement than with force (Bertero and Bertero, 2002), engineers cannot rely solely on force-based methods for intended building performance levels. While FBD has generally provided safe structures, it hasn't ensured uniform damage across structure. In response to this situation, Performance-Based Design methods emerged over the past twenty years, ensures that structures behave predictably under specific seismic hazards. The limitations of FBD have prompted the development of performance-based design methodologies, like Displacement-Based Design (Qi and Moehle, 1991), Direct Displacement-Based Design (Priestley, 1993; Xue, 2001; Sullivan *et.al.*, 2005, 2006), which prioritize actual structural behavior during earthquakes. These approaches focus on limiting displacements and enhancing overall performance and safety. By understanding both traditional and emerging seismic design methods, engineers can better prepare structures for seismic challenges.

UPBD offers a direct method for determining beam depths and column sizes at the start of the design, significantly reducing computational effort and eliminating the need for iterative member resizing. The major highlight of this UPBD method is a straightforward formula for choosing the optimal beam depth that meets the target objectives, which greatly minimizes the computational workload during the design process (Choudhury and Singh, 2013). For the selection of appropriate column sizes in UPBD method, Mayengbam and Choudhury (2012, 2014) developed a procedure based on a wide range of different parameters; elastic and average shear displacement of column, yield and joint shear rotation of beams along with the design drift. Manisana and Mayengbam (2024a, 2004b) modified the procedure for Base-Isolated RCC Frame Buildings. In Performance-Based Design (PBD), performance levels outline how a structure is expected to behave during particular hazard events. Building performance levels are characterized by damage levels indicated by factors such as inelastic rotation in members and crack width. The typical performance levels include Immediate Occupancy (IO) - minimal damage, Life Safety (LS) - moderate damage with no risk to life during strong ground motion, and Collapse Prevention (CP) - significant damage approaching structural collapse.

The building materials considered in the previous UPBD studies are M30 concrete and Fe415 rebar steel for RCC frame buildings by Mayengbam and Choudhury (2012, 2014); M25 concrete and Fe415 for Base-Isolated RCC Frame Buildings by Manisana and Mayengbam (2024a, 2004b). The primary objective of this study is to check the validity of UPBD for RCC frame buildings under different ranges of common design considerations including M20 concrete and Fe500 rebar steel. In this study, UPBD methodology is applied to RCC frame building structures of varying heights; 2, 4, 6, and 8 stories. The design IDR considered are 1%, 2% and

3%. RCC materials considered are M20 concrete and steel grades Fe415 & Fe500. The frames are analyzed and designed using SAP2000 v16.1. EC-8 (2004) design displacement spectrum at 0.45g seismicity level and type B soil condition are considered.

## 2. Methodology

The beam depths are obtained as per Choudhury and Singh (2013), given in Equation (1). Here;  $h_b$  is beam depth,  $\varepsilon_y$  is yield strain of rebar steel,  $l_b$  is length of beam,  $\theta_d$  is interstorey drift, and  $\theta_{pb}$  is average plastic hinge rotation in beam.

$$h_b = \frac{0.5\varepsilon_y l_b}{\theta_d - \theta_{pb}} \quad (1)$$

The sizes of columns are derived as per Mayengbam and Choudhury (2014), given in Equation (2). Here  $\theta_{dr}$  is design IDR,  $a_d$  is the dynamic amplification of IDR,  $h_b$  is beam depth,  $\varepsilon_y$  is yield strain of rebar steel,  $l_b$  is length of beam,  $\theta_{ta}$  is the achieved IDR,  $a_m$  and  $a_s$  are the dynamic amplification of column moment and shear respectively,  $l_c$  is the length of column within a storey,  $h_c$  is the column depth in the direction of earthquake under consideration,  $l_{cc}$  is the distance between the point of contra flexure and the point of maximum bending moment,  $f_b$  is contribution of bond slip,  $V$  is the maximum shear force applied to member,  $\nu$  is the Poisson's ratio,  $c_r$  is the ratio of column depth to column width and  $E$  is the Young's modulus of elasticity. Equation (3) gives the plastic hinge rotation of beam ( $\theta_{bp}$ ) in terms of achieved storey drift ( $\theta_{ta}$ ).

$$\{\theta_{dr} a_d - \frac{0.35375\varepsilon_y l_b}{h_b} - \theta_{bp}\} l_c h_c^2 - (a_m + f_b) 0.7\varepsilon_y l_{cc}^2 h_c - \frac{24V(1+\nu)c_r a_s}{0.9E} = 0 \quad (2)$$

$$\theta_{bp} = 0.00616\theta_{ta} - 0.00402 \quad (3)$$

The target design IDR and performance criteria for the building are first fixed. The plastic rotation is taken as the average permissible plastic rotation that corresponds to the desired performance level provided by FEMA-356. The beam width is taken between one-third and half of its depth, following typical design practices. After determining the member size, DDBD is used to calculate the design lateral forces at each floor level.

Expected strength gives mean strength not limit strength. Expected strengths of concrete and rebar steel are taken as  $1.5f_{ck}$  and  $1.25f_y$  (FEMA-356) respectively. Here,  $f_{ck}$  and  $f_y$  are the characteristic strengths of concrete and rebar steel respectively. The design load combination is taken as maximum of;  $(D + L)$ ,  $(D + L \pm F_x)$  and  $(D + L \pm F_y)$ . Here;  $D$ ,  $L$ , represent dead load

and live load respectively;  $F_x$  and  $F_y$  represent the seismic loads in the two orthogonal directions of the building.

The buildings are designed for specific target IDRs and performance levels. To ensure proper plastic hinge mechanism utilizing the RCC's ductile behavior, strong-column weak-beam capacity design is applied in addition to the DDBD design demand. The column-to-beam capacity ratio (C/B ratio) at each beam-column joint is maintained to at least 1.3, except at roof level where this requirement is not applicable.

The performances of the designed buildings are checked with NLTHA using Spectrum Compatible Ground Motions (SCGM).

Table 1: Design considerations.

| Particulars                               |        | Values |
|-------------------------------------------|--------|--------|
| Slab thickness (m)                        |        | 0.14   |
| Concrete unit weight (kN/m <sup>3</sup> ) |        | 25     |
| Live load (kN/m <sup>2</sup> )            |        | 2      |
| Parapet height (m)                        |        | 1      |
| Roof live (kN/m <sup>2</sup> )            |        | 1.5    |
| Wall thickness (m)                        |        | 0.125  |
| Brick unit weight (kN/m <sup>3</sup> )    |        | 20     |
| Moment modification factor (IS1893)       | column | 0.7    |
|                                           | beam   | 0.35   |

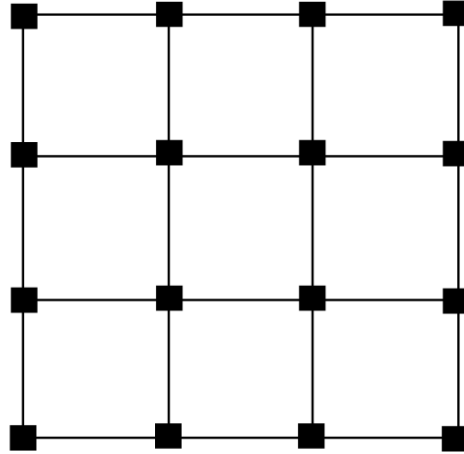


Figure 1: Building Plan considered in present study.

### 3. Analysis and Design considerations

The buildings have a common plan having 3 bays and a regular geometry with same span of 6 meters in both the orthogonal direction as shown in Figure 1. The buildings are of different heights; 2-storey, 4-storey, 6-storey and 8-storey with design IDRs; 1%, 2% and 3% IDR. A

common floor height of 3.3 meters is taken. Material used in design include concrete of cube strength 20 MPa and reinforcing rebar steel of yield strengths of 415 Mpa and 500 Mpa. For both materials, expected strengths are used as per FEMA-356. Other design considerations are given in Table (1). The buildings are modeled, designed and analyzed using SAP2000 v.16.1. The member sizes and calculated floor masses are given in Tables (2) and (3) respectively. Design Displacement spectrum used is that of EC-8 corresponding to soil type B and 0.45g seismicity level shown in Figure 2. The corner period extension of 5 seconds is applied.

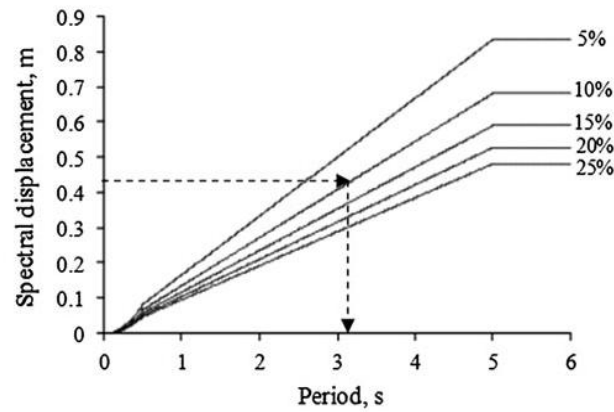


Figure 2: Design Displacement spectra for various damping

Table 2: Beam and column size.

| Design Drift (%) | Buildings (storey) | Beam size (mm × mm) | Floor wise column depths in mm (square column) |                 |                 |                 |                 |                 |                 |                 |
|------------------|--------------------|---------------------|------------------------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  |                    |                     | 1 <sup>st</sup>                                | 2 <sup>nd</sup> | 3 <sup>rd</sup> | 4 <sup>th</sup> | 5 <sup>th</sup> | 6 <sup>th</sup> | 7 <sup>th</sup> | 8 <sup>th</sup> |
| 1                | 2                  | 1200 × 620          | 735                                            | 640             |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 1200 × 620          | 810                                            | 755             | 675             | 640             |                 |                 |                 |                 |
|                  | 6                  | 1200 × 620          | 860                                            | 825             | 745             | 685             | 640             | 640             |                 |                 |
|                  | 8                  | 1200 × 620          | 920                                            | 880             | 800             | 740             | 685             | 675             | 660             | 640             |
| 2                | 2                  | 760 × 390           | 540                                            | 470             |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 760 × 390           | 640                                            | 600             | 530             | 490             |                 |                 |                 |                 |
|                  | 6                  | 780 × 400           | 655                                            | 625             | 560             | 520             | 490             | 485             |                 |                 |
|                  | 8                  | 780 × 400           | 735                                            | 700             | 630             | 585             | 540             | 535             | 530             | 530             |
| 3                | 2                  | 600 × 320           | 405                                            | 355             |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 600 × 320           | 510                                            | 470             | 420             | 390             |                 |                 |                 |                 |
|                  | 6                  | 630 × 350           | 520                                            | 495             | 445             | 410             | 385             | 385             |                 |                 |
|                  | 8                  | 630 × 350           | 590                                            | 560             | 500             | 465             | 430             | 430             | 430             | 425             |

Table 3: Floor masses.

| Design drift (%) | Buildings (storey) | Floor masses (kilo Newton) |                 |                 |                 |                 |                 |                 |                 |
|------------------|--------------------|----------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                  |                    | 1 <sup>st</sup>            | 2 <sup>nd</sup> | 3 <sup>rd</sup> | 4 <sup>th</sup> | 5 <sup>th</sup> | 6 <sup>th</sup> | 7 <sup>th</sup> | 8 <sup>th</sup> |
| 1                | 2                  | 681.39                     | 495.02          |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 696.98                     | 685.41          | 670.02          | 495.02          |                 |                 |                 |                 |
|                  | 6                  | 708.22                     | 700.28          | 683.39          | 671.85          | 663.82          | 495.02          |                 |                 |
|                  | 8                  | 722.58                     | 712.89          | 694.82          | 682.39          | 671.85          | 670.02          | 670.38          | 495.02          |
| 2                | 2                  | 483.74                     | 305.43          |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 499.62                     | 492.94          | 482.30          | 308.01          |                 |                 |                 |                 |
|                  | 6                  | 507.95                     | 502.78          | 492.42          | 486.62          | 482.54          | 313.07          |                 |                 |
|                  | 8                  | 522.91                     | 516.15          | 503.63          | 496.27          | 489.47          | 488.74          | 488.03          | 319.22          |
| 3                | 2                  | 428.28                     | 254.36          |                 |                 |                 |                 |                 |                 |
|                  | 4                  | 441.21                     | 435.93          | 429.95          | 257.87          |                 |                 |                 |                 |
|                  | 6                  | 453.05                     | 449.63          | 443.31          | 439.28          | 436.61          | 267.81          |                 |                 |
|                  | 8                  | 463.49                     | 458.86          | 450.30          | 445.75          | 441.55          | 441.55          | 441.54          | 272.16          |

Table 4: DDBD parameters for buildings steel grade Fe500.

| Design drift (%) | Buildings | $\Delta_d$ (m) | $m_e$ (kN) | $H_e$ (m) | $\mu$ | $\xi$ (%) | $T_e$ (s) | $K_e$ (kN) | Stability ratio | Design base shear (kN) |
|------------------|-----------|----------------|------------|-----------|-------|-----------|-----------|------------|-----------------|------------------------|
| 1                | 2         | 0.0525         | 1049.67    | 5.25      | 1.280 | 9.44      | 0.434     | 220006.3   | 0.0089          | 11560.59               |
|                  | 4         | 0.0947         | 2110.44    | 9.47      | 1.280 | 9.44      | 0.679     | 180661.1   | 0.0121          | 17113.44               |
|                  | 6         | 0.1129         | 3307.72    | 13.41     | 1.078 | 6.42      | 0.716     | 254396.6   | 0.0095          | 28742.34               |
|                  | 8         | 0.1474         | 4403.02    | 17.63     | 1.070 | 6.27      | 0.927     | 20326.6    | 0.0121          | 29962.68               |
| 2                | 2         | 0.1028         | 702.51     | 5.14      | 1.621 | 13.19     | 0.818     | 41417.8    | 0.0323          | 4263.04                |
|                  | 4         | 0.1861         | 1477.19    | 9.30      | 1.621 | 13.19     | 1.502     | 25839.41   | 0.0603          | 4826.45                |
|                  | 6         | 0.2240         | 2349.53    | 13.25     | 1.406 | 10.98     | 1.690     | 32464.83   | 0.0535          | 7286.57                |
|                  | 8         | 0.2928         | 3166.28    | 17.48     | 1.394 | 10.84     | 2.189     | 26077.07   | 0.0681          | 7662.85                |
| 3                | 2         | 0.1527         | 607.28     | 5.09      | 1.920 | 15.63     | 1.317     | 13891.9    | 0.0842          | 2146.78                |
|                  | 4         | 0.2773         | 1297.48    | 9.24      | 1.92  | 15.63     | 2.363     | 9171.90    | 0.1501          | 2644.05                |
|                  | 6         | 0.3352         | 2101.96    | 13.21     | 1.705 | 13.94     | 2.721     | 11209.64   | 0.1392          | 3857.28                |
|                  | 8         | 0.4387         | 2831.56    | 17.45     | 1.689 | 13.81     | 3.414     | 9591.45    | 0.1659          | 4367.84                |

Computed DDBD design parameters for buildings with rebar steel grade Fe500 & Fe415 are given in Tables 4 and 5 respectively. In some aspects lower grade rebar steel are better higher grades rebar steel. As given in the Tables 4 and 5 that the Fe415 buildings have more ductility, damping, time period; and less stiffness, stability and design base shear than those of the Fe500 buildings.

Table 5: DDBD parameters for buildings with steel grade Fe415.

| Design drift (%) | Buildings | $\Delta_d$ (m) | $m_e$ (kN) | $H_e$ (m) | $\mu$ | $\xi$ (%) | $T_e$ (s) | $K_e$ (kN) | Stability ratio | Design base shear (kN) |
|------------------|-----------|----------------|------------|-----------|-------|-----------|-----------|------------|-----------------|------------------------|
| 1                | 2         | 0.0525         | 1049.67    | 5.25      | 1.542 | 12.43     | 0.462     | 193979.1   | 0.0010          | 10193.01               |
|                  | 4         | 0.0947         | 2110.44    | 9.47      | 1.542 | 12.43     | 0.740     | 151943.4   | 0.0144          | 14393.90               |
|                  | 6         | 0.1129         | 3307.22    | 13.41     | 1.299 | 9.68      | 0.808     | 200035.6   | 0.0121          | 22600.86               |
|                  | 8         | 0.1474         | 4403.02    | 17.63     | 1.289 | 9.55      | 1.057     | 155586.2   | 0.0157          | 2293.29                |
| 2                | 2         | 0.1028         | 702.51     | 5.14      | 1.953 | 15.87     | 0.876     | 36091.9    | 0.0371          | 3718.66                |
|                  | 4         | 0.1861         | 1477.19    | 9.30      | 1.953 | 15.87     | 1.606     | 22598.97   | 0.0689          | 4237.86                |
|                  | 6         | 0.2240         | 2349.53    | 13.25     | 1.694 | 13.85     | 1.832     | 27645.98   | 0.0628          | 6222.01                |
|                  | 8         | 0.2928         | 3166.28    | 17.48     | 1.679 | 13.72     | 2.377     | 22115.90   | 0.0803          | 6529.07                |
| 3                | 2         | 0.1527         | 607.28     | 5.09      | 2.313 | 18.08     | 1.390     | 12408.6    | 0.0942          | 1934.34                |
|                  | 4         | 0.2773         | 1297.48    | 9.24      | 2.313 | 18.08     | 2.496     | 8219.24    | 0.1675          | 2431.29                |
|                  | 6         | 0.3352         | 2101.96    | 13.21     | 2.054 | 16.54     | 2.885     | 9968.57    | 0.1566          | 3503.16                |
|                  | 8         | 0.4387         | 2831.56    | 17.45     | 2.036 | 16.42     | 3.585     | 8698.73    | 0.1830          | 4067.84                |

A typical column interaction curve at expected strength level and limit strength level for a column of the 6-storey building designed with 1% target IDR is shown in Figure 3. The background earthquake considered for generating the SCGM is the Duzce (1999) earthquake record no. 270(ERD). It had a magnitude of 7.2 and a duration 25.9 seconds. The SCGM incorporates the phase angle, frequency characteristics, and duration of the background earthquake. The purpose of implementing SCGM is to guarantee that the nonlinear evaluation of the buildings is performed at the same hazard level as that used during the design phase. This study follows the performance and drift combinations that the Immediate Occupancy (IO), Life Safety (LS) and Collapse Prevention (CP) performance level hinges form when IDR vary from 1% to 1.5%, 1.5% to 2.5%, exceeds 2.5% respectively.

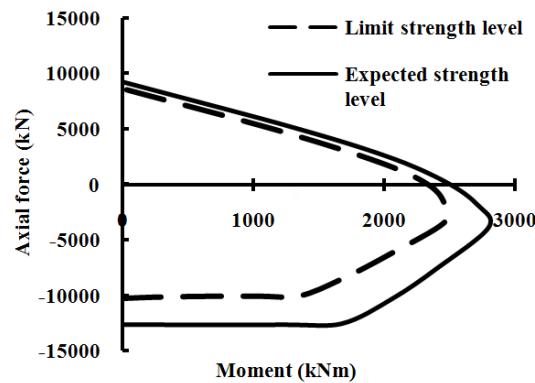


Figure 3: A typical column interaction curve at expected strength level and limit strength level for 6-storey of 1% IDR of column size 745 × 745 mm.

#### 4. Results and Discussion (Validation)

In this section, the buildings designed as per sections 2 and 3 are validated for their target IDR and performance level. The amount of beam plastic rotation with respect to the achieved IDR is also checked. Typical plastic hinge pictures in the structural members of 2, 4, 6 & 8-storey frames buildings with rebar steel grades Fe500 & Fe415 are shown in Figures 4, 5, 6 and 7 respectively. The performance level of the building is determined by the types of plastic hinges develop in the frame members. It can be observed that buildings with target IDR 1%, 2% and 3% achieve performance levels of IO, LS and CP respectively, except in case of the 8 storey building with target IDR 3% in which the performance level is conservative achieving LS, within CP. The hinge patterns indicate that the desired performance levels for each building are successfully achieved.

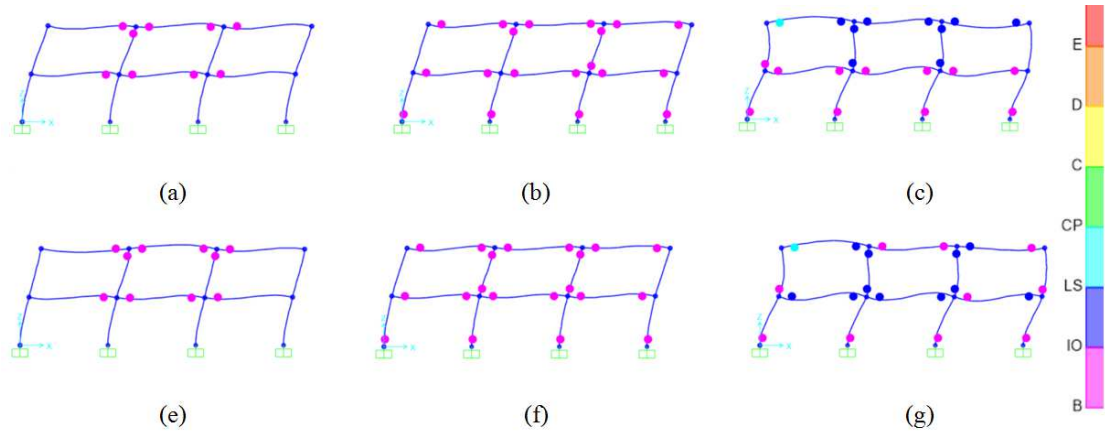


Figure 4: Typical plastic hinge pictures 2 storey; Fe500 buildings (a) 1% (b) 2% and (c) 3% target IDR, Fe415 buildings (e) 1% (f) 2% and (g) 3% target IDR.

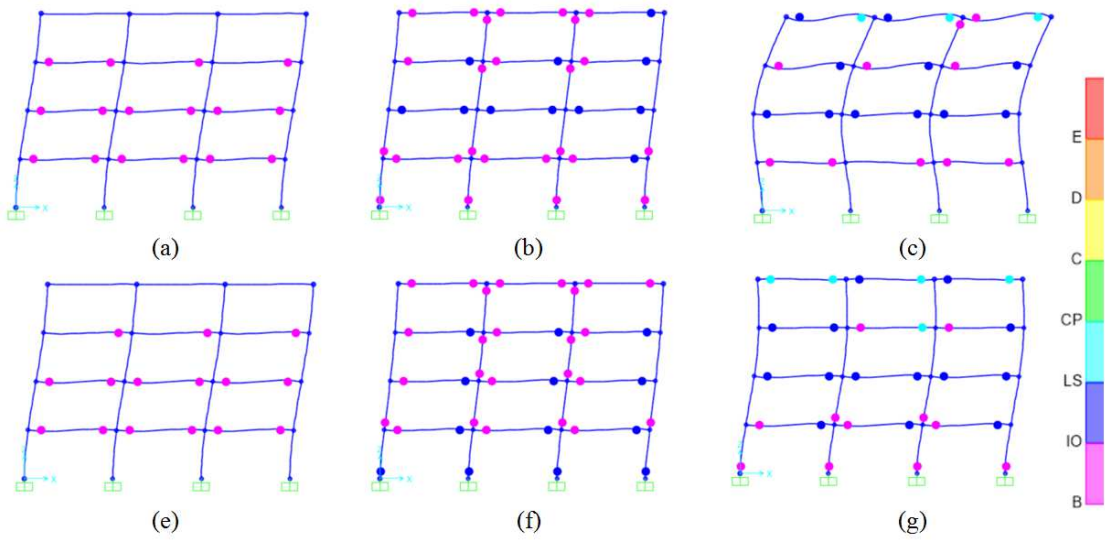


Figure 5: Typical plastic hinge pictures for 4 storey; Fe500 buildings (a) 1% (b) 2% and (c) 3% target IDR, Fe415 buildings (a) 1% (b) 2% and (c) 3% target IDR.

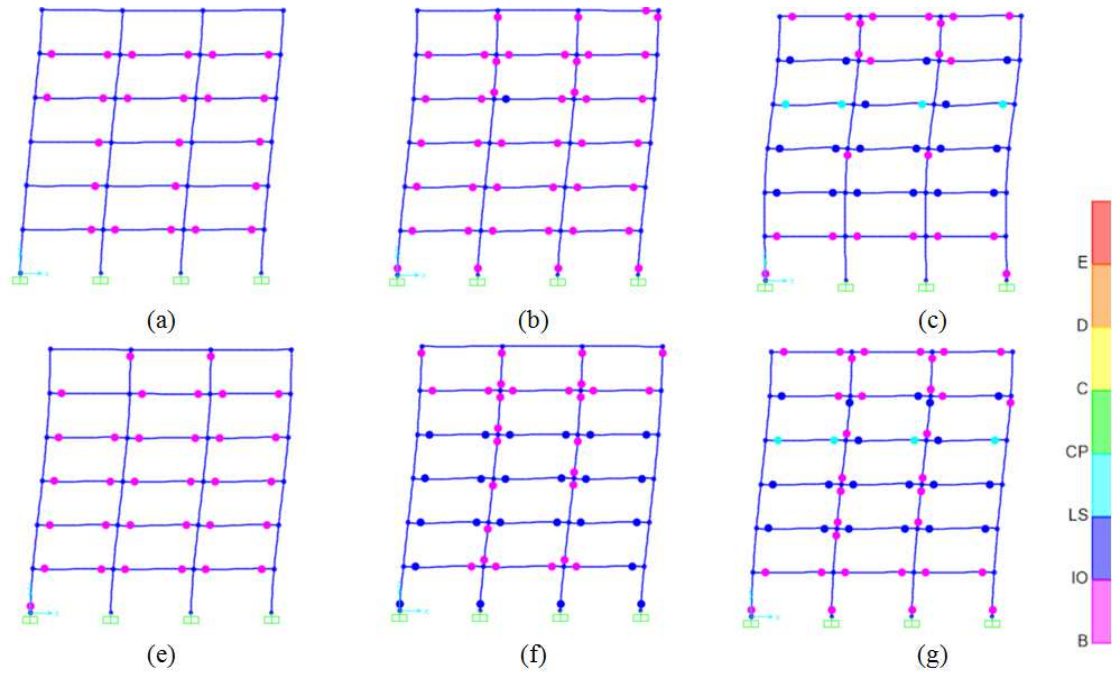


Figure 6: Typical plastic hinge pictures for 6 storey; Fe500 buildings (a) 1% (b) 2% and (c) 3% target IDR, Fe415 buildings (a) 1% (b) 2% and (c) 3% target IDR.

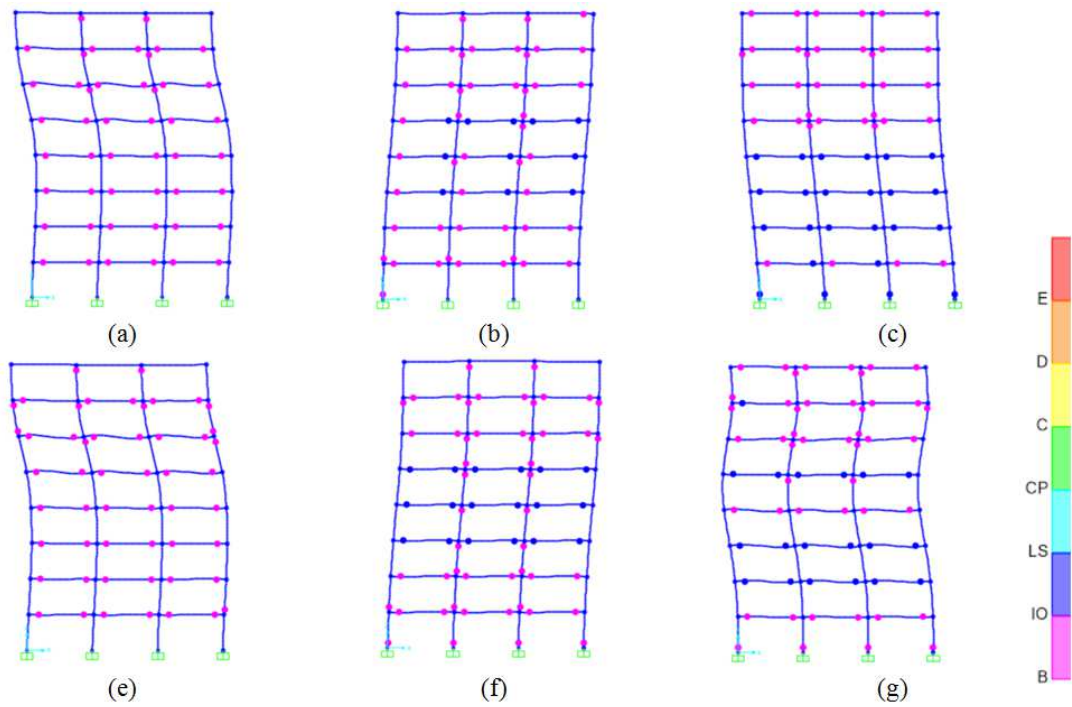


Figure 7: Typical plastic hinge pictures for 8 storey; Fe500 buildings (a) 1% (b) 2% and (c) 3% target IDR, Fe415 buildings (a) 1% (b) 2% and (c) 3% target IDR.

IDR is derived from the floor displacement response histories of NLTHA. IDR diagrams for 2, 4, 6 & 8-storey frames buildings with rebar steel grades Fe500 & Fe415 are shown in Figures 8, 9, 10 and 11 respectively.

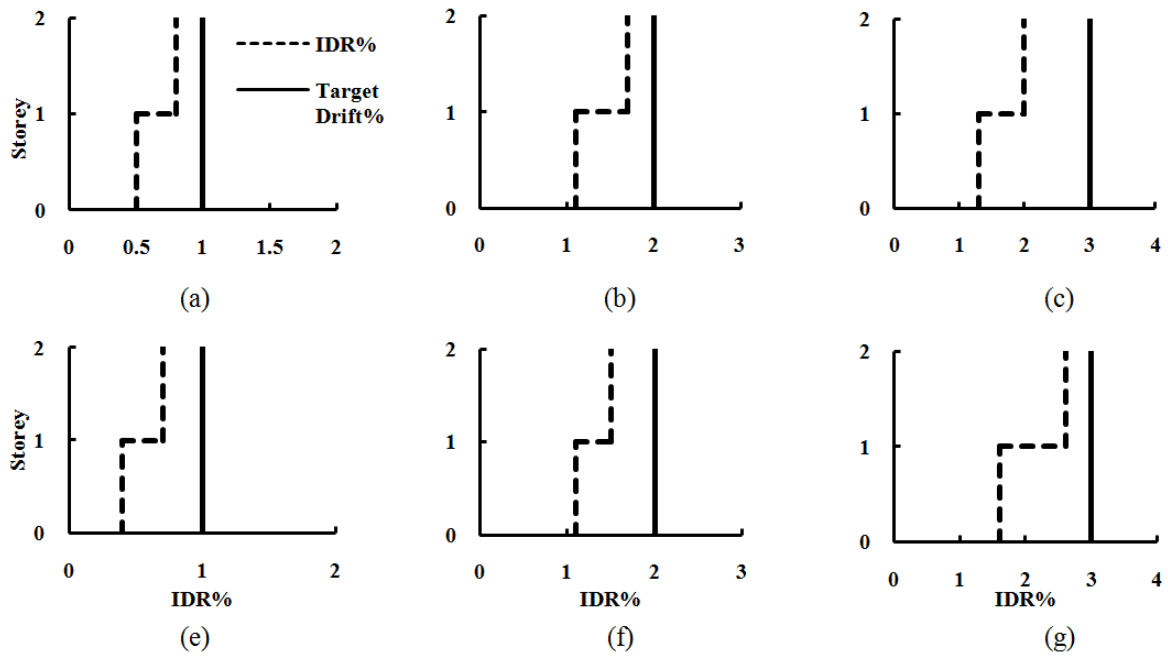


Figure 8: IDR plot for 2 storey; Fe500 buildings (a) 1%, (b) 2% and (c) 3% target IDR; Fe415 buildings (e) 1%, (f) 2% and (g) 3% target IDR.

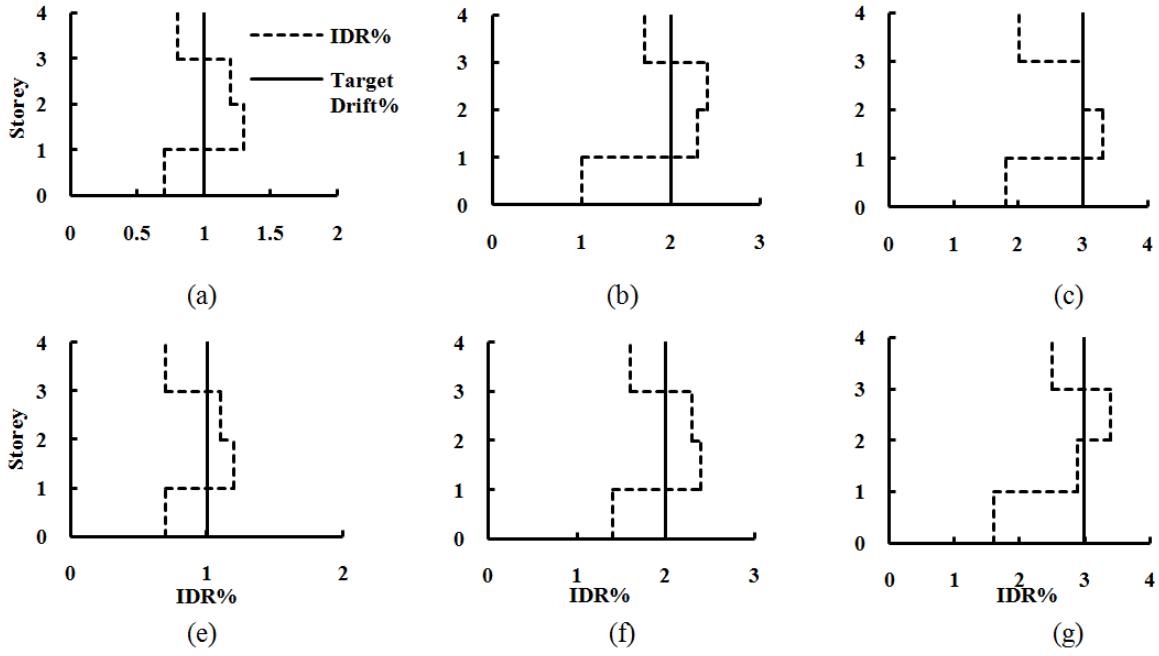


Figure 9: IDR plot for 4 storey; Fe500 buildings (a) 1%, (b) 2% and (c) 3% target IDR; Fe415 buildings (e) 1%, (f) 2% and (g) 3% target IDR.

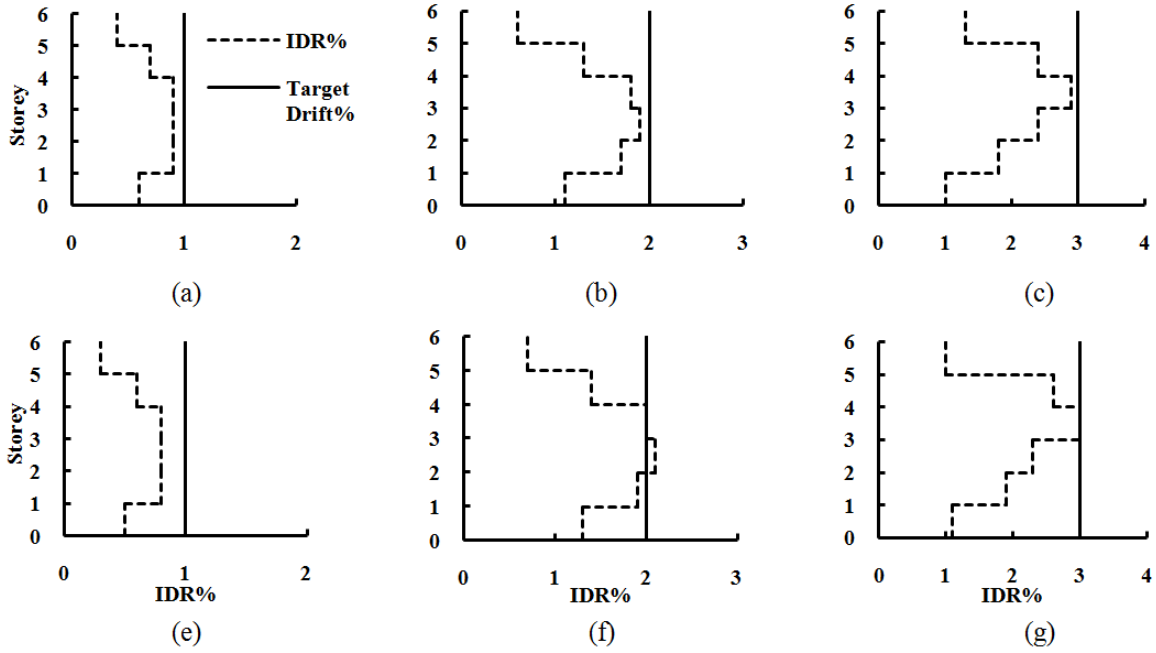


Figure 10: IDR plot for 6 storey; Fe500 buildings (a) 1%, (b) 2% and (c) 3% target IDR; Fe415 buildings (e) 1%, (f) 2% and (g) 3% target IDR.

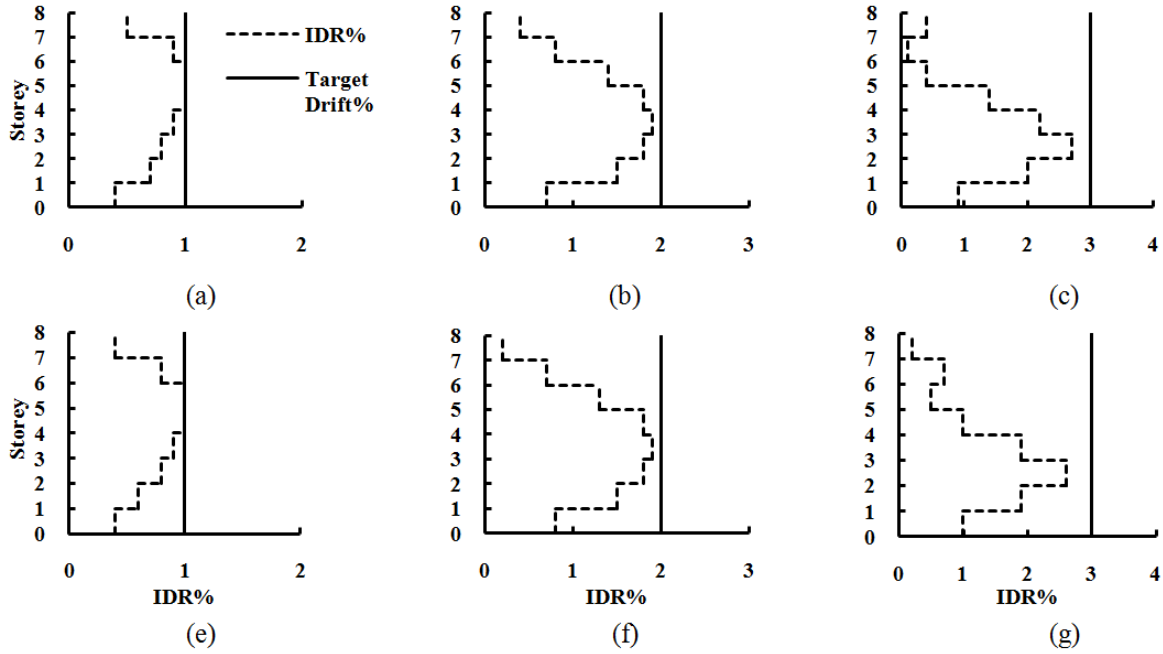


Figure 11: IDR plot for 8 storey; Fe500 buildings (a) 1%, (b) 2% and (c) 3% target IDR; Fe415 buildings (e) 1%, (f) 2% and (g) 3% target IDR.

Tables 6 and 7 give the overall achieved performance level and IDR for the buildings with rebar steel grade Fe500 & Fe415 respectively. It can be observed that the IDR has been achieved with maximum exceedance of 0.4% beyond the target drift, which well within tolerance limit. The maximum achieved plastic hinge rotation in beam members and the plastic hinge rotations in the beam members derived from the Equation 3 are also given in Tables 6 and 7.

Table 6: Achieved performance level and achieved drift for buildings with steel grade Fe500.

| Target<br>IDR (%) | Buildings | Performance level |          | Achieved<br>Maximum<br>drift (%) | Maximum<br>deviation<br>from target<br>drift (%) | Maximum<br>Achieved<br>$\phi_{bp} \times 10^{-2}$<br>(radian) | Equation (3)<br>$\phi_{bp} \times 10^{-2}$<br>(radian) | Moment<br>(kNm) |
|-------------------|-----------|-------------------|----------|----------------------------------|--------------------------------------------------|---------------------------------------------------------------|--------------------------------------------------------|-----------------|
|                   |           | Target            | Achieved |                                  |                                                  |                                                               |                                                        |                 |
| 1                 | 2         | IO                | IO       | 0.8                              | -0.2                                             | 0.0766                                                        | 0.0908                                                 | 250.62          |
|                   | 4         | IO                | IO       | 1.3                              | 0.3                                              | 0.3477                                                        | 0.3988                                                 | 1294.6          |
|                   | 6         | IO                | IO       | 0.9                              | -0.1                                             | 0.0655                                                        | 0.1524                                                 | 1136.8          |
|                   | 8         | IO                | IO       | 1                                | 0.0                                              | 0.4255                                                        | 0.2140                                                 | 1343.6          |
| 2                 | 2         | LS                | LS       | 1.7                              | -0.3                                             | 0.8583                                                        | 0.6452                                                 | 327.22          |
|                   | 4         | LS                | LS       | 2.4                              | 0.4                                              | 1.1435                                                        | 1.0764                                                 | 297.84          |
|                   | 6         | LS                | LS       | 1.9                              | -0.1                                             | 1.0007                                                        | 0.7684                                                 | 397.71          |
|                   | 8         | LS                | LS       | 1.9                              | -0.1                                             | 1.0604                                                        | 0.7684                                                 | 510.9           |
| 3                 | 2         | CP                | CP       | 3                                | 0.0                                              | 1.3973                                                        | 1.4460                                                 | 172.61          |
|                   | 4         | CP                | CP       | 3.3                              | 0.3                                              | 1.8358                                                        | 1.6308                                                 | 273.99          |
|                   | 6         | CP                | CP       | 2.9                              | -0.1                                             | 1.6669                                                        | 1.3844                                                 | 240.73          |
|                   | 8         | CP                | LS       | 2.7                              | -0.3                                             | 1.2798                                                        | 1.2612                                                 | 385.04          |

Table 7: Achieved performance level and achieved drift for buildings with steel grade Fe415.

| Target drift (%) | Buildings | Performance level |          | Achieved Maximum drift (%) | Maximum deviation from target drift (%) | Maximum Achieved $\phi_{bp} \times 10^{-2}$ (radian) | Equation (3) $\phi_{bp} \times 10^{-2}$ (radian) | Moment (kNm) |
|------------------|-----------|-------------------|----------|----------------------------|-----------------------------------------|------------------------------------------------------|--------------------------------------------------|--------------|
|                  |           | Target            | Achieved |                            |                                         |                                                      |                                                  |              |
| 1                | 2         | IO                | IO       | 0.7                        | -0.30                                   | 0.0521                                               | 0.0292                                           | 290.10       |
|                  | 4         | IO                | IO       | 1.2                        | 0.20                                    | 0.3589                                               | 0.3372                                           | 1178.6       |
|                  | 6         | IO                | IO       | 0.8                        | -0.20                                   | 0.2117                                               | 0.0908                                           | 1469.2       |
|                  | 8         | IO                | IO       | 1.0                        | 0.0                                     | 0.5663                                               | 0.214                                            | 1266.5       |
| 2                | 2         | LS                | LS       | 1.5                        | -0.5                                    | 0.7528                                               | 0.5220                                           | 346.78       |
|                  | 4         | LS                | LS       | 2.4                        | 0.40                                    | 1.2396                                               | 1.0764                                           | 394.36       |
|                  | 6         | LS                | LS       | 2.1                        | 0.10                                    | 1.3637                                               | 0.8916                                           | 600.97       |
|                  | 8         | LS                | LS       | 1.9                        | -0.10                                   | 1.1565                                               | 0.7684                                           | 641.79       |
| 3                | 2         | CP                | CP       | 2.6                        | -0.40                                   | 1.3153                                               | 1.1996                                           | 160.98       |
|                  | 4         | CP                | CP       | 3.4                        | 0.40                                    | 1.8645                                               | 1.6924                                           | 153.84       |
|                  | 6         | CP                | CP       | 3.0                        | 0.0                                     | 1.7608                                               | 1.4460                                           | 223.85       |
|                  | 8         | CP                | LS       | 2.6                        | -0.40                                   | 1.2997                                               | 1.1996                                           | 283.98       |

Figures 12a and 12b show plots of achieved IDR *Vs.* beam plastic rotation for buildings with Fe500 and Fe415 rebar steel respectively, linear regression of the plots are given in Equations 4 and 5 respectively.

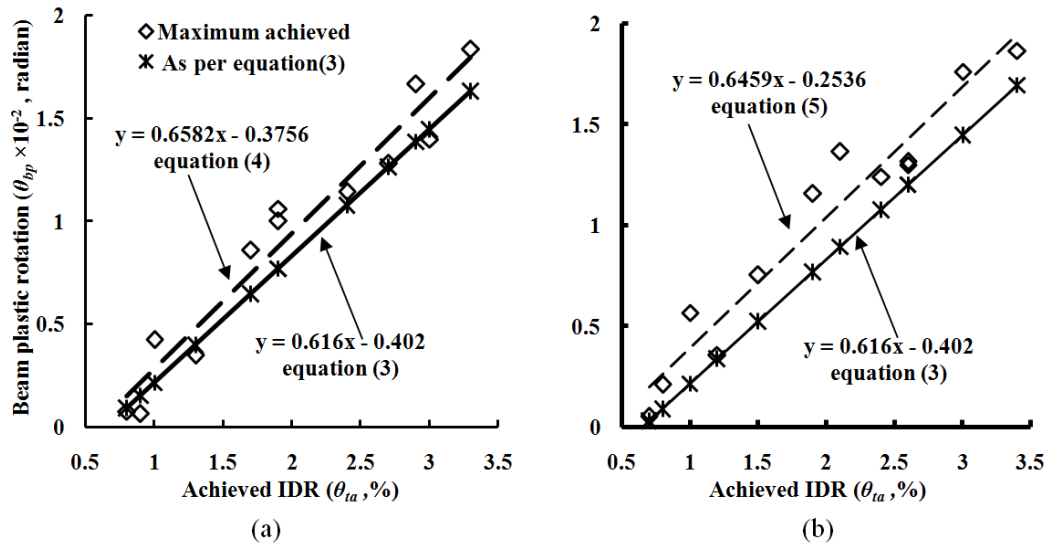


Figure 12: Achieved IDR *Vs.* beam plastic rotation for buildings with; (a) Fe500 and (b) Fe415 rebar steel.

$$\theta_{bp} = 0.6582\theta_{ta} - 0.3756 \quad (4)$$

$$\theta_{bp} = 0.6459\theta_{ta} - 0.2536 \quad (5)$$

The plots show an increasing trend, indicating that larger drift ratios correspond to higher beam plastic rotations. Equations 4 and 5 are in good terms with Equation 3. The average

deviations of Equations 4 and 5 lines from Equation 3 are  $0.110 \times 10^{-2}$  and  $0.206 \times 10^{-2}$  radians respectively.

## 5. Conclusion

The findings of this study confirms the effectiveness of UPBD methodology under varying design conditions; heights (2, 4, 6, and 8 stories), IDRs of 1%, 2%, and 3%, concrete grade M20 and steel grades (Fe415 and Fe500). Displacement spectra corresponding to EC-8 design spectra for soil type B and seismicity level of 0.45g are used. The design strategy effectively reduces iterative processes by offering direct sizing methods for beams and columns, improving design speed and accuracy. Validation through NLTHA assures the reliability of the design, as the achieved drift and hinge formations aligned with the targeted performance objectives. Furthermore, the weak-beam strong-column requirement is also maintained, promoting ductile failure modes and enhancing the seismic performance of the structures. The target design IDRs are achieved with a very small maximum exceedance of 0.4% beyond the target IDR in few cases, which is well within tolerance limit. The variations of plastic hinge patterns are in good terms with the existing one, with small average deviations of  $0.110 \times 10^{-2}$  and  $0.206 \times 10^{-2}$  radians for the buildings with Fe415 and Fe500 concrete respectively. Overall, the findings affirm that the UPBD approach can be used effectively as a practical methodology for designing earthquake-resistant RCC structures within the scope of the existing and the present study for predefined performance objectives.

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**Author Contributions:** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by the first author. The first draft of the manuscript including the figures and tables was prepared by the first author. The Manuscript including the figures and tables was organized systematically and refined by the second author. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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