Unified Performance-Based Design of RC Dual System

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Research Article

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UNIFIED PERFORMANCE-BASED DESIGN OF RC DUAL SYSTEM

ABSTRACT

A dual system building is comprised of frames and shear walls. In dual system the shear wall predominantly carries the lateral loads arising out of earthquake or wind. Frame is primarily designed for vertical load along with a fraction of lateral load. The force-based method of design or codal design method can hardly design building for pre-defined target objectives. The alternative method of design is displacement-based design (DBD). Available displacement-based design, like, Direct Displacement-Based design (DDBD) had been applied to dual system. However, DDBD method satisfied only drift criteria and was silent about the performance level. Also, the member sizes had to be obtained through iterations. Unified Performance-Based Design (UPBD) method can accommodate both drift and performance level as target design criteria. In the present study the theoretical background of UPBD method for dual system has been explained and detailed design steps have been highlighted. The method has been validated through several dual system buildings with different target design criteria. Dual system buildings have been designed using UPBD method for target objectives of (i) Immediate Occupancy performance level (PL) with drift 1%, (ii) life Safety PL with drift 2% and, (iii) Collapse Prevention PL with drift 3%. The nonlinear evaluation of the designed buildings shows that in all the cases the target design criteria have been fulfilled. The UPBD method of dual system also gives the member sizes in the beginning of the design and thus avoids iteration in design.

KEYWORDS
Dual system, Performance-Based Design, Unified Performance-Based Design, Layered shell element, Drift, Performance level.

1. INTRODUCTION

A dual system building, also known as frame-shear wall building, is very efficient in carrying lateral load arising out of earthquake or wind. Shear wall resists the lateral loads through in-plane action. Frame primarily takes vertical load along with a fraction of the lateral load. Shear wall also dissipates a large amount of energy absorbed from the ground motion, through hysteresis. Shear wall can be modeled as mid-pier element, large column element as well as element with shell (Harman and Henderson 1985, Kalkan and Chopra 2011, Looi et al. 2017). Clough et al. (1964) proposed 2D model frame termed as wide column analogy
that gained popularity. Further, Akis et al. (2018) proposed two different 3D models of shear wall which were with open and closed sections; but it could not give accurate behavior of a shear wall. The importance of proper modeling of shear wall for both linear and nonlinear analysis was highlighted (Ozkula et al. 2019, Pejovic et.al 2018). A recently developed model of shear wall is layered shear wall (Kubin et al. 2008, Fahjan 2010). The benefit of modeling shear wall as layered shell elements is that it can tackle shear wall of large size in 3D models. As far as position of the shear walls in plan is concerned, the position in the mid-length of plan dimension was found to decrease the displacement and increase the performance (Chandurkar et al. 2013, Tarigan et al. 2018) and therefore layered shell elements have been used in the present study. Conventional codal method of design of dual system is essentially force-based, that is, it involves computing base shear compatible to the design spectrum and distributing the base shear over floors and then designing the system for these distributed forces. No attention is given to performance of the system in terms of drift or performance level. In fact, designing the system for a given target performance through codal method is almost impossible (possible through large numbers of trials). The alternative method of design is displacement-based design (DBD) or performance-based design (PBD) which can accommodate target design criteria in the design process. Direct Displacement-Based Design (DDBD) for reinforced concrete (RC) frame buildings (Pettinga and Priestley 2005) and dual system (Sullivan et al. 2006) are easy to use and effective in satisfying target criterion. But the limitation of the DDBD method is that it can fulfill only one target criterion, namely, design drift. The performance level (PL), which is equally important design criterion, is not addressed in this design approach. UPBD method for RC frame buildings was developed by Choudhury and Singh (2013). In the UPBD design, member sizes are obtained in the beginning of the design by satisfying target criteria of both drift and performance level (in relation to plastic rotation in designated members) simultaneously. Das and Choudhury (2019) investigated the effect of effective stiffness in RC frame buildings designed using UPBD method and found that gross stiffness or FEMA-specified stiffness are inadequate in capturing true dynamic response of such buildings. In the current study, the applicability of the UPBD method for dual system for different target performance objectives has been explored. In the present study dual system buildings of 2 plans and 4 height categories (8-, 10-, 12- and 15-storey) have been considered with target design criteria as (i) Immediate Occupancy (IO) PL with 1% drift, (ii) Life Safety (LS) PL with 2% drift and, (iii) Collapse Prevention (CP) PL with 3% drift. These drift limits have been assumed as per FEMA-356 (2000, Table C1-3). The design as well as nonlinear evaluation of buildings has been carried out separately in two major directions of each plan. The nonlinear hinge properties have been used as per ASCE 41-13 (2014), Performance-Based Design (PBD) is damage-based design and hence MCE level of seismicity is taken in PBD for design and analysis. The considered buildings have been designed using UPBD method with EC-8 (2004) design spectrum at 0.45g seismicity level and type B soil condition. The designed buildings have been evaluated through nonlinear analyses under spectrum compatible ground motions (SCGM) corresponding to the same design spectrum. For the generation of SCGMs, five background earthquakes have been selected based on magnitude range of 4.9 to 7.9 (Peer 2015-11, Kalkan and Chopra 2011). The SCGMs have been generated using the software developed by Kumar (Kumar 2004).

2. DESIGN PHILOSOPHY IN UPBD METHOD FOR FRAME-SHEAR WALL BUILDINGS
The force-based design (FBD) method or codal design method considers the force as the core design parameter. In FBD it is difficult to achieve any target design criteria (like drift, plastic rotation and crack width) without going through large number of iterations, as member sizes are unknown in the beginning of the design. Displacement-based design (DBD) and PBD are the alternative methods of design approach which can address the target design criteria. The available DDBD method for RC frame buildings (Pettinga and Priestley 2005) and DDBD method for dual system (Sullivan et al. 2006) can address only drift as single design criterion. These two methods are silent about member PL. Also the member sizes are obtained through iteration. UPBD method on the other hand can take care of two performance criteria, namely, drift and performance level (in terms of plastic rotation in members). In addition to this UPBD method also gives member sizes in the beginning of the design so that iteration is avoided. The sizes of beams are obtained as per Choudhury and Singh (2013) and length of shear wall and thickness of shear wall are obtained through a formulation as discussed in section 2.1.

2.1 Computation of wall length and wall thickness

A multiple degree of freedom system can be converted to an equivalent single degree of freedom (ESDOF) system (Priestley 2007) as shown in Fig. 1b. In Fig. 1b, \( h_e \) stands for effective height of ESDOF system, \( m_e \) stands for equivalent mass. The target interstorey drift (\( \theta_d \)) of MDOF system is equivalent to the total rotation of ESDOF system. This can be considered as equivalent rotational drift. As shear wall is predominant member in dual system, the total rotation of the ESDOF system comprises of yield rotation (\( \theta_{yw} \)) and plastic rotation (\( \theta_{pw} \)) of the wall. The relationship amongst rotational angles is given by Eq. (1).

\[
\theta_d = \theta_{yw} + \theta_{pw}
\] (1)

![Fig.1](a) MDOF system (b) ESDOF system.

The yield rotation of wall is given by Eq. (2) and yield curvature of wall (\( \phi_{yw} \)) is given by Eq. (3) (Priestley et.al 2007).

\[
\theta_{yw} = \frac{\phi_{yw} h_{inf}}{2}
\] (2)

\[
\phi_{yw} = \frac{2\gamma_y}{L_w}
\] (3)
In Eq. (2), \( h_{inf} \) is inflection height of wall. In Eq. (3), \( \varepsilon_y \) yield strain of rebar in wall, and \( L_w \) is the horizontal length of the wall. Substituting Eq. (2) and Eq. (3) in Eq. (1), Eq. (4) is obtained.

\[
L_w = \frac{\varepsilon_y h_{inf}}{\theta_d - \theta_{pw}} \tag{4}
\]

Eq. (4) gives the length of the wall that simultaneously satisfies the drift criterion and performance level criterion (plastic rotation in wall). In the above formulation, \( \theta_d \) is target design inter-storey drift. Plastic rotation of wall (\( \theta_{pw} \)) values are taken as averages of allowed plastic rotation given in ASCE 41-13 for wall with boundary elements. The total lateral shear is carried by the shear wall and frame. Typically, 25% to 35% lateral shear is assumed to be taken by the frame. Eq. (5) shows the apportionment of total shear in wall and frame.

\[
\frac{V_{wall,i}}{V_b} = \frac{V_{total,i}}{V_b} - \frac{V_{frame,i}}{V_b} \tag{5}
\]

Where, \( V_{wall,i} \) is the shear carried by wall in \( i \)-th storey in the direction considered, \( V_{total,i} \) is the total shears at floor \( i \), \( V_{frame,i} \) is the shear to be carried by the \( i \)-th frame and, \( V_b \) is the design base shear.

The thickness of wall (\( t_w \)) is obtained from base shear taken by walls and number of walls used in a particular direction, as shown in Eq. (6).

\[
t_w = \frac{V_{Wall}}{0.8 \times L_w \times \tau_c \times N_w} \tag{6}
\]

Where, \( V_{Wall} \) is shear carried by the walls in the direction under consideration, \( \tau_c \) is permissible shear stress of concrete, and \( N_w \) is the number of walls in the direction under consideration, \( L_w \) is horizontal length of wall. The factor 0.8 is used to reflect the fact that 80% of the wall length is considered as effective in taking shear (IS 456 2000).

2.2 Calculation of plastic rotation of wall

In the present study, the shear wall has been modeled as layered shell element. In Nonlinear analysis, the layered shell element exhibits plasticity characteristics as a distributed plasticity and there is no formation of visible lumped plastic hinges as in normal cases of frame elements. So, the plastic rotation in the wall is to be computed in an indirect way, as described here. The plastic rotation of the wall can be obtained from moment-rotation diagrams. Moment-rotation response can be obtained by plotting section cut forces and generalized displacement to provide moment versus rotation graph in a hysteresis loop (Fig. 15). The plastic rotation of the layered shear wall can be found out by noting the rotation of shear wall in the ground storey level, where the plasticity is maximum. Maximum rotation of wall (\( \theta_{max} \)) is obtained from moment rotation diagram as shown in Fig. 15. Plastic rotation of wall can now be obtained from the Eq. (7). Needless to say, \( \theta_{yw} \) is obtained from Eq. (2).

\[
\theta_{pw} = \theta_{max} - \theta_{yw} \tag{7}
\]

2.3 Interpretation of the equation for length of wall (Eq. (4))
Eq. (4) can be used to express the ratio of length of wall to inflection height ($\frac{L_w}{h_{inf}}$) for varying drift values and PL (i.e., wall inelastic rotations) as depicted in Fig. 2. The interpretation of Fig. 2 is discussed in this paragraph. Large drift means more damage and hence lower performance level. The combination of drift and PL should be judiciously chosen so that higher PL is combined with lower drift, and lower PL is combined with higher drift. It has been assumed here in line with FEMA 356 that drift compatible to IO PL varies from 1% to 1.5%, that compatible to LS PL varies from 1.5% to 2.5%, and for CP PL it varies from 2.5% to 4%. The Upper limits of $\frac{L_w}{h_{inf}}$ is obtained by putting the plastic rotation of wall ($\theta_{pw}$) (displayed in Table 1) corresponding to desired PL and by varying drifts in Eq. (4). With reference to Fig. 2, curve PQ, RST and UVW are upper limit curves drawn for all the performance levels using Eq. (4). For length of wall within zone RS, $\frac{L_w}{h_{inf}}$ are same as that under IO level and hence, such length of walls will be uneconomical for LS level, being a lower PL than IO. Thus, line QS is drawn horizontally denoting the boundary of LS level. With similar arguments, the length UV is uneconomical for CP performance level and line TV is drawn horizontally denoting boundary of CP. Finally, the curve PQSTVW provides the upper limit of wall length for various combinations of drifts and performance levels. When the value of plastic rotation of wall ($\theta_{pw}$) is set to zero, Eq. (4) gives the lower limit of wall size which shows no damage taking place in the wall thereby dictating elastic behavior. The area between the two bounds shown in hatching gives the region of viable ratio of wall lengths to inflection height. The Fig. 2 is typically drawn for yield strength of rebar for 500 MPa and, for other yield strengths similar curves can be drawn. Consequently, the approach suggested is not restricted to Fig. 2. For a specified grouping of performance level and drift, various ratios of $\frac{L_w}{h_{inf}}$ within upper limits and lower limits (i.e. the hatched area) can be used. Theoretical upper limit indicates a condition in which shear wall develops full plastic rotation. As the plastic rotation decreases, the elastic rotation increases within the design drift limit and the lower limits of wall length shows an elastic behavior. The upper and lower limits of lengths of wall for the considered building are presented in Table 1.

![Fig 2. Graphical representation of relation between ratio of length of wall and height of inflection with varying drift.](image)

**Table 1:** Limits of wall lengths for various drifts and PLs considered in the study
3. DESIGN PROCEDURE AS PER UPBD METHOD
The step wise procedure for designing frame-shear wall building using UPBD method is given below.

**Step 1: Computation of member sizes**
The design target drift ($\theta_d$) and performance level (in terms of plastic rotation of wall and beam) are decided. The hazard level is considered. Infection height is computed. The wall length satisfying the target criteria is given by Eq. (4) which is repeated as Eq. (8) here. Alternatively, $L_w/h_{inf}$ ratio can be obtained from graph shown in Fig. 2, and $L_w$ can be computed knowing the value of $h_{inf}$.

$$L_w = \frac{\varepsilon_y h_{inf}}{\theta_d - \theta_{pw}}$$  \hspace{1cm} (8)

The beam depth satisfying the target criteria is given by Eq. (9) (Choudhury and Singh, 2013).

$$h_b = \frac{0.5\varepsilon_y l_b}{\theta_d - \theta_{pb}}$$  \hspace{1cm} (9)

In Eq. (9), $l_b$ is length of beam in the direction of seismic action, $\theta_{pb}$ is allowable plastic rotation of beam for the PL considered (available from ASCE-SEI-41-13 and FEMA-356). The width of beam is taken as half to two-third of beam depth as per common practice. Column size is found out by trial so that the column steel remains in the range 3% to 4% of the gross sectional area of column. This is the practical range of steel in column avoiding over-crowding of bars. Alternatively, the column size can be obtained after (Mayengbam and Choudhury 2014).

**Step 2: Computation of ESDOF system properties**
The MDOF building is converted to ESDOF system using formulae given as Eq. (10) to (13) (Sullivan et al. 2006).

\[
\Delta_d = \frac{\sum_{i=1}^{N} m_i \Delta_i^2}{\sum_{i=1}^{N} m_i \Delta_i} \tag{10}
\]

\[
m_e = \frac{\sum_{i=1}^{N} m_i \Delta_i}{\Delta_d} \tag{11}
\]

\[
h_e = \frac{\sum_{i=1}^{N} m_i \Delta_i h_i}{\sum_{i=1}^{N} m_i \Delta_i} \tag{12}
\]

\[
\Delta_i = \Delta_{iyw} + \left( \theta_d - \phi_{yw} h_{inf}/2 \right) h_i \tag{13}
\]

Where, \(\Delta_d\) is the design displacement, \(m_e\) is the effective mass, \(h_e\) is the equivalent height of the ESDOF system; \(m_i\) is the mass of \(i\)-th storey, \(\Delta_{iyw}\) is the yield displacements of wall in \(i\)-th storey, \(h_i\) is the height of \(i\)-th floor from the base of the building, \(\Delta_i\) is the profile displacement in the \(i\)-th floor and, \(N\) is the number of storey in the building. The yield displacement profile of wall is obtained using Eq. (14).

\[
\Delta_{iyw} = \frac{\phi_{yw} h_{inf}}{2} - \frac{\phi_{yw} h_{inf}^3}{6}, \text{ when } h_i \geq h_{inf} \tag{14a}
\]

\[
\Delta_{iyw} = \frac{\phi_{yw} h_{inf}^2}{2} - \frac{\phi_{yw} h_{inf}^3}{6h_{inf}}, \text{ when } h_i \leq h_{inf} \tag{14b}
\]

\[
\phi_{yw} = \frac{2e_y}{L_w} \tag{14c}
\]

**Step 3: Computation of height of inflection of wall**

The height of the inflection \((h_{inf})\) is a design parameter in dual system design. Inflection point is where the curvature of the building reverses due to frame-shear wall interaction. The height of inflection of frame shear wall can be determined by identifying the moments that are borne by shear wall. The vertical distribution of the moment of the wall is determined by subtracting the frame moments from the total moments. The detailed process can be seen in (Priestley et. al.2007). A typical drawing for inflection height is shown in Fig. 3.
Step 4: Ductility of wall and frame
Ductility demands of frames and walls can be determined by using Eq. (15) and Eq. (16) (Sullivan et al. 2006).

\[
\mu_w = \frac{\Delta d}{\Delta h_{e,y}} \quad (15)
\]

\[
\mu_f = \left(\frac{\Delta_i - \Delta_{i-1}}{h_i - h_{i-1}}\right) \frac{1}{\theta_{yf}} \quad (16)
\]

Where, \(\mu_w\) is the displacement ductility of wall, \(\Delta h_{e,y}\) is the yield displacement of the wall at the effective height level, \(\Delta_{i-1}\) is the displacements at \((i-1)\)-th floor, \(h_{i-1}\) is the heights of \((i-1)\)-th floor, \(\mu_f\) is the displacement ductility of frame and, \(\theta_{yf}\) is the frame yield drift.

Step 5: Computation of equivalent damping of ESDOF system
In the year 2005, Blandon and Priestley (further developed by Grant et al., 2005) had recommended that equivalent damping be computed as a function of the effective time period. As at the start of design the effective time period is not known, therefore, a trial value can be used and an iteration design process can be adopted. The value of the trial effective period is given by Eq. (17).

\[
T_{e,\text{trial}} = \frac{N}{6} \sqrt{\mu_{sys}} \quad (17)
\]

\[
\mu_{sys} = \frac{M_w\mu_w + M_{ot,f}\mu_f}{M_w + M_{ot,f}} \quad (18)
\]

Where, \(N\) is number of storey of building, and \(\mu_{sys}\) is ESDOF system ductility. From the set of effective time period and computed ductility values, equivalent viscous dampings of wall and frame are evaluated using Eqn. (19) and (20) respectively.
\[
\xi_w = \frac{95}{1.3\pi} (1 - \mu_w^{0.5} - 0.1 \times r \times \mu_w) \left( \frac{1}{(T_{e,trial} + 0.85)^{\frac{1}{2}}} \right) \quad (19)
\]
\[
\xi_f = \frac{120}{1.3\pi} (1 - \mu_w^{0.5} - 0.1 \times r \times \mu_f) \left( 1 + \frac{1}{(T_{e,trial} + 0.85)^{\frac{1}{2}}} \right) \quad (20)
\]

The equivalent damping of ESDOF system is obtained from Eq. (21).

\[
\xi_{SDoF} = \frac{M_w \xi_w + M_{ot,f} \xi_f}{M_w + M_{ot,f}} \quad (21)
\]

Here, \(M_w\) is wall moment, \(\xi_w\) is wall damping, \(M_{ot,f}\) is overturning moment of frames, \(\xi_f\) is frame damping, \(T_{e,trial}\) is trial effective time period, and \(r\) is the post yield stiffness ratio, generally taken as 0.05 for new RC structures.

**Step 6: Computation of effective stiffness from displacement spectra**

Displacement spectra corresponding to design spectra are drawn for various damping values. For this purpose, Eq. (22) is utilized. Here, \(\eta\) is reduction factor corresponding to the damping. Displacement spectra corresponding to (EC-82004)design spectra for soil type B and at 0.45g level has been shown in Fig. 4.

\[
\eta = \sqrt{\frac{10}{(5 + \xi_{ESDOF})}} \geq 0.55 \quad (22)
\]

**Fig. 4** Displacement Spectra corresponding to EC-8 design spectra for soil type B at 0.45g level.

Effective stiffness \(K_e\) found by the Eq. (23)

\[
K_e = \frac{4\pi^2 m_e}{T_e^2} \quad (23)
\]

**Step 7: Base shear computation and its distribution**

The base shear \(V_b\) is expressed as per Eq. (24)
\[ V_b = K_e \Delta_d \]  \hspace{1cm} (24)

The computed base shear is distributed to different floors as per Eq. (25)

\[ F_i = V_b \frac{m_i \Delta_i}{\sum_{i=1}^{n} m_i \Delta_i} \]  \hspace{1cm} (25)

Where, \( F_i \) is the force applied to different floors of the buildings. The base shear computation and its distribution shall be done in both the mutually perpendicular directions of the plan of the building. The Eq. (25) is valid upto 10-storey high buildings. For buildings taller than ten storey, 90% of base shear is distributed in all floors including the roof level as per Eq. (25); the remaining 10% of base shear is put at roof level. This is done to take care of higher mode effects in tall buildings.

**Step 8: Load combination and design**

The combinations of load used for design are:

\[
\begin{align*}
&DL + LL \\
&DL + LL \pm F_x \\
&DL + LL \pm F_y
\end{align*}
\]

Where \( DL, LL, F_x, F_y \) stand for dead load, live load, earthquake load in \( x \) direction and earthquake load in \( y \) direction respectively. It may be noted that DDBD or UPBD method of design are damaged based design. As such partial safety factor as used in limit state design are not applicable. For the same reason expected strength of materials are used. Capacity design is carried out so that column to beam capacity ratio is more than 1.4 (IS 13920-2016; this is 1.3 as per EC-8).

### 4. MODELING ASPECTS

#### 4.1 Shear wall modeling

The shear wall has been modeled as layered shell element. In shell element the steel bar can provided in either one layer or two layers. Rigid beam elements are assumed in the beam level. There is a tendency of normal beams embedded within shear wall get damaged thereby distorting the normal shear wall behavior. The rigid beam element prevents this unwanted behavior of wall. The purpose of rigid element is also to reduce the mesh resistance formulations. It also gives proper connection with adjacent beams and columns. These aspects are shown in Fig. 5 and 6. The modulus of elasticity of rigid beams is taken about 10 times the modulus of elasticity of concrete (Kubin et al. 2008, Fahjan et al. 2010). ASCE-SEI-41-13 gives the plastic rotation of shear wall for various performance levels. Debnath and Choudhury (2017) performed a nonlinear shell element component study and attempted to understand its performance for LS buildings.
4.2 Moment rotation response of RC nonlinear hinges

The nonlinear hinges in member have been provided as per ASCE-SEI-41-13. The nonlinear response behavior has been furnished in Fig. 7, which is implemented in default hinges of SAP2000 v.21.

5. NOMENCLATURE OF THE BUILDINGS AND TARGET DESIGN CRITERIA CONSIDERED IN THE STUDY
5.1 Buildings considered

In the current study, 12 dual system buildings have been considered with two different plans, namely, plan I and plan II (Fig.8). The heights of buildings considered are 8-, 10-, 12- and 15-storeys. The buildings have been designed using UPBD method for target performance objectives of: (i) IO PL with 1% drift, (ii) LS PL with 2% drift and, (iii) CP PL with 3% drift. Design spectrum used is that of EC-8 corresponding to soil type B and 0.45g seismicity level. SAP2000 v.21 software was used to model, design and analyze the buildings. Concrete of characteristic cube strength 30 MPa and rebar of yield strength of 500 MPa have been used. The foundation of the building has been considered as rigid resting on soil type B of Eurocode-8. The height of each storey is kept constant to 3.1 m. The column steel was restricted within 3% to 4% to maintain uniformity in the buildings. The building nomenclature is shown in Table 2.
Building name starts with ‘B’ and contains number of storey and PL (IO, LS or CP). The sizes of member used in buildings have been given in Table 3. As an example, for the building \textbf{B-15-CP} length of wall has taken as 12 m, which lies between the upper limit and lower limits (Table 1). To show any length of wall within this limit works, the length of wall for building \textbf{B-12-CP} have been taken as 10 m. Likewise, the length of wall of other buildings has been taken within limits of Table 1. The computed ESDOF system properties are given in Table 4. As per FEMA-356, the expected strength of concrete is taken as 1.5 times the characteristics strength, and, expected strength of rebar is taken as 1.25 times the yield strength of rebar.

\textbf{Table 2: Nomenclature of the buildings and target design criteria considered}

| Sl No. | Plan of the Building | Nomenclature of Buildings | Target performance level | Target drift |
|--------|----------------------|---------------------------|--------------------------|-------------|
| 1      | I                    | B-8-IO                    | IO                       | 1%          |
| 2      | I                    | B-10-IO                   |                          |             |
| 3      | I                    | B-12-IO                   |                          |             |
| 4      | I                    | B-15-IO                   |                          |             |
| 5      | I                    | B-8-LS                    | LS                       | 2%          |
| 6      | II                   | B-10-LS                   |                          |             |
| 7      | II                   | B-12-LS                   |                          |             |
| 8      | II                   | B-15-LS                   |                          |             |
| 9      | II                   | B-8-CP                    | CP                       | 3%          |
| 10     | II                   | B-10-CP                   |                          |             |
| 11     | II                   | B-12-CP                   |                          |             |
| 12     | II                   | B-15-CP                   |                          |             |
### Table 3: Dimensions of members of the buildings considered

| Building name | Inner Column | Outer column | Beam size (mm) | Shear wall thickness (mm) | Length of wall (mm) |
|---------------|--------------|--------------|----------------|--------------------------|---------------------|
|               | Column sizes (mm) | Beam size (mm) | Shear wall thickness (mm) | Length of wall (mm) |
| B-8-IO        | 800 × 800 | 900 × 900 | 850 × 850 | 800 × 800 | 500 × 1000 | 150 | 3000 |
| B-10-IO       | 600 × 600 | 700 × 700 | 650 × 650 | 600 × 600 | 350 × 500 | 300 | 3500 |
| B-12-IO       | 600 × 600 | 700 × 700 | 650 × 650 | 600 × 600 | 400 × 600 | 300 | 4000 |
| B-15-IO       | 800 × 800 | 800 × 800 | 850 × 850 | 900 × 900 | 500 × 1000 | 300 | 5000 |
| B-8-LS        | 700 × 700 | 800 × 800 | 750 × 750 | 700 × 700 | 450 × 700 | 150 | 5000 |
| B-10-LS       | 550 × 550 | 650 × 650 | 600 × 600 | 550 × 550 | 400 × 700 | 300 | 6000 |
| B-12-LS       | 650 × 650 | 750 × 750 | 700 × 700 | 650 × 650 | 450 × 900 | 300 | 7000 |
| B-15-LS       | 700 × 700 | 800 × 800 | 750 × 750 | 730 × 730 | 350 × 600 | 300 | 8000 |
| B-8-CP        | 600 × 600 | 700 × 700 | 650 × 650 | 600 × 600 | 350 × 500 | 150 | 7000 |
| B-10-CP       | 600 × 600 | 700 × 700 | 650 × 650 | 600 × 600 | 350 × 500 | 200 | 8000 |
| B-12-CP       | 600 × 600 | 700 × 700 | 650 × 650 | 600 × 600 | 450 × 650 | 200 | 10000 |
| B-15-CP       | 730 × 730 | 780 × 780 | 750 × 750 | 730 × 730 | 500 × 750 | 300 | 12000 |

### Table 4: ESDOF system properties for buildings designed

| Buildings | $\Delta_d$ | $m_e$ | $k_e$ | $\xi_w$ | $\xi_f$ | $\mu$ | $T_e$ | $K_e$ | $V_b$ |
|-----------|------------|-------|-------|---------|---------|-------|-------|-------|-------|
|           | m         | kg    | sec   | %       | %       | wall  | frame | kN/m  | kN    |
| B-8-IO    | 0.247     | 2109150 | 17.669 | 8.16 | 17.15 | 2.377 | 6.71 | 2.9 | 9890787 | 2447 |
| B-10-IO   | 0.400     | 3340535 | 23.137 | 9.29 | 10.35 | 2.776 | 2.46 | 2.6 | 1948960 | 7799 |
| B-12-IO   | 0.557     | 3149765 | 25.835 | 10.67 | 7.06 | 3.419 | 1.77 | 2.9 | 14770714 | 8229 |
| B-15-IO   | 0.733     | 6874082 | 32.198 | 11.71 | 9.50 | 4.097 | 2.24 | 3.8 | 18774433 | 13770 |
| B-8-LS    | 0.283     | 3108391 | 17.209 | 9.69 | 7.77 | 2.944 | 1.89 | 2.9 | 14576692 | 4127 |
| B-10-LS   | 0.322     | 3774809 | 21.220 | 9.33 | 8.63 | 2.792 | 2.05 | 2.6 | 22022553 | 7093 |
| B-12-LS   | 0.424     | 6659832 | 25.532 | 8.96 | 7.83 | 2.652 | 1.9 | 2.9 | 31231051 | 13249 |
| B-15-LS   | 0.610     | 7705276 | 40.301 | 8.54 | 7.34 | 2.502 | 1.81 | 3.6 | 23447823 | 14318 |
| B-8-CP    | 0.314     | 2358018 | 17.929 | 12.08 | 3.56 | 4.347 | 1.31 | 2.9 | 11057844 | 3482 |
| B-10-CP   | 0.366     | 3961201 | 21.089 | 9.674 | 9.37 | 2.935 | 2.20 | 2.6 | 23109979 | 8474 |
| B-12-CP   | 0.439     | 5912479 | 25.351 | 9.303 | 7.42 | 2.781 | 1.82 | 2.9 | 27726365 | 12199 |
| B-15-CP   | 0.556     | 13898194 | 31.589 | 10.05 | 9.50 | 3.109 | 2.24 | 3.8 | 37958626 | 21125 |
5.2 Hazard Consideration
In the displacement-based design displacement spectra corresponding to the design spectrum is used. In the present study the displacement spectra corresponding to EC-8 (2004) design spectra for soil type B at 0.45g seismicity level has been considered. In the displacement spectra, corner period is extended up to 5 sec, as per Pettinga and Priestley 2005. In the present study, background earthquakes for generation of SCGM have been selected based on magnitude in the range of 4.9-7.9 (PEER 2015, Kalkan and Chopra 2011). For the nonlinear dynamic analysis, five SCGMs have been used which are generated using Kumar (2004) software. The software requires a background earthquake to generate artificial ground motion. Such background earthquakes are tabulated in Table 5. A typical SCGM is shown in Fig. 9. The match of response spectra out of SCGMs with EC-8 demand spectra is shown in Fig. 10. The main purpose of using SCGM is to confirm that nonlinear assessment of buildings is carried out at the same hazard level for which it has been designed.

Table 5: Spectrum Compatible ground motions considered

| Sl.No. | Name of SCGM | Background Eq. (India) | Year of occurrence | Durations in sec |
|--------|---------------|------------------------|--------------------|-----------------|
| 1      | GM1           | Baithalangso           | 1988               | 78.05           |
| 2      | GM2           | Nonghklaw              | 1986               | 29.54           |
| 3      | GM3           | Silchar                | 1988               | 46.81           |
| 4      | GM4           | Umsning                | 1981               | 70.52           |
| 5      | GM5           | Barkot                 | 1991               | 31.61           |

Fig.9 Typical spectrum compatible ground motion: GM1.
6. RESULTS AND DISCUSSIONS

Plastic rotations of the frame members are checked by observing the hinge patterns. In SAP2000 v.21 software, the frame member’s show lumped plastic hinges and the performance level of the hinges can be identified by the color of the hinges. As shown in Table 3, total 12 frame-shear wall buildings have been designed in this study using UPBD method, and evaluated through nonlinear analyses. The hinge formation at MCE level in frame elements for typical frames are shown in Fig. 11. The hinge patterns show that the target performance levels for respective buildings have been achieved.
Fig. 11 Plastic hinges for typical building frames at end of time history analysis.

The performance level for the buildings can also be read out from the pushover analysis. The performance point encompassed by a nearest performance level designator in the capacity curve gives the performance level of the building. In Fig. 12, the typical pushover curves have been presented. The pushover curves show that the target performance level of IO and LS have been achieved in the respective buildings.
Fig. 12 Pushover curves of typical buildings at the end of time history analysis.

The inter-storey drift ratio (IDR) can be obtained from displacement time histories of floors. In Fig. 13 the IDR diagram for typical buildings are presented. From the figures it is clear that the target drifts have been achieved with marginal deviation.
In SAP2000 v.21 software, layered shear wall does not show lumped plastic hinge. The non-linear behavior of layered shell element can be identified by stresses in concrete and stresses in reinforcement. In Fig. 14, the stresses in reinforcement along the height of wall are shown. The expected yield strength of rebar is $500 \times 1.25$ or $625$ N/mm$^2$. Wherever this stress is exceeded it can be understood that the rebar has yielded and plasticity had set in. The value of yield rotation in wall is computed using Eq. (7). From maximum rotation, the yield rotation is to be subtracted to get the plastic rotation of wall. The maximum rotation of wall is obtained as discussed below.
The maximum rotation in shear wall can be determined by plotting section cut forces and generalized displacements which in turn provides the moment versus rotation graph in a hysteresis loop as shown in Fig.15. From these graphs the maximum rotation of wall can be determined. The plastic rotation is obtained by subtracting the yield rotation from total rotation. Table 6 shows the computed plastic rotation of shear walls of different buildings and also it shows that the actual plastic rotations are within the limits of target values.
Fig. 15: Moment-rotation diagram for typical layered shear wall model.

Table 6: Target vs. achieved plastic rotation of shear walls

| Building names | Target PL | Target plastic rotation of wall (ASCE 41-13) (rad) | Maximum rotation of wall at ground storey (rad) | Yield rotation of wall (rad) | Achieved Plastic rotation of wall (rad) |
|----------------|-----------|-------------------------------------------------|-----------------------------------------------|----------------------------|-----------------------------------|
| (1)            | (2)       | (3)                                             | (4)                                           | (5)                        | (6) = (4)-(5)                     |
| B-8-IO         | IO        | 0.00375                                         | 0.0163                                        | 0.0038                      |
| B-10-IO        | IO        | 0.0170                                          | 0.0147                                        | 0.0023                      |
| B-12-IO        | IO        | 0.0147                                          | 0.0123                                        | 0.0024                      |
| B-15-IO        | IO        | 0.0199                                          | 0.0169                                        | 0.0030                      |
| B-8-LS         | LS        | 0.00975                                         | 0.0098                                        | 0.0087                      |
| B-10-LS        | LS        | 0.0142                                          | 0.0070                                        | 0.0072                      |
| B-12-LS        | LS        | 0.0160                                          | 0.0070                                        | 0.0089                      |
| B-15-LS        | LS        | 0.0121                                          | 0.0061                                        | 0.0060                      |
| B-8-CP         | CP        | 0.01425                                         | 0.0061                                        | 0.0041                      |
| B-10-CP        | CP        | 0.0270                                          | 0.0061                                        | 0.0209                      |
| B-12-CP        | CP        | 0.0230                                          | 0.0076                                        | 0.0154                      |
| B-15-CP        | CP        | 0.0153                                          | 0.0041                                        | 0.0112                      |

Table 7 shows a summary of the achieved target objectives. As shown in the table, the interstorey drifts are within ±13% of target drifts, which is tolerable.

Table 7: Target versus achieved building performances

| Building names | Target objectives | | Achieved performances | Maximum Drift % | Deviation of drift from the target |
|----------------|-------------------|------------------|---------------------|-----------------|-----------------------------------|
| Building names | Target objectives | | Performance level (PL) | Drift, % | Short direction | Long direction | Drift (%) | |
| (1)            | (2)               | (3)              | (4)                 | (5)            | (6)           | (7)          | (8)       |                  |
| B-8-IO         | IO                | 1.0              | IO                  | 0.89           | 0.91          | 0.91         | -9 %      |
| B-10-IO        | IO                | 1.0              | IO                  | 0.90           | 0.93          | 0.93         | -7 %      |
| B-12-IO        | IO                | 1.0              | IO                  | 0.97           | 0.98          | 0.98         | -2 %      |
| B-15-IO        | IO                | 1.0              | IO                  | 0.87           | 0.87          | 0.87         | -13%      |
| B-8-LS         | LS                | 2.0              | LS                  | 1.98           | 1.96          | 1.98         | -2%       |
| B-10-LS        | LS                | 2.0              | LS                  | 2.20           | 2.20          | 2.20         | +10%      |
| B-12-LS        | LS                | 2.0              | LS                  | 2.13           | 2.06          | 2.13         | +6.5%     |
| B-15-LS        | LS                | 2.0              | LS                  | 1.81           | 1.63          | 1.81         | -9.5%     |
| B-8-CP         | CP                | 3.0              | CP                  | 3.01           | 2.97          | 3.01         | +3.3%     |
| B-10-CP        | CP                | 3.0              | CP                  | 2.98           | 2.98          | 2.98         | -6.6%     |
| B-12-CP        | CP                | 3.0              | CP                  | 2.97           | 2.75          | 2.97         | -0.7%     |
| B-15-CP        | CP                | 3.0              | CP                  | 2.31           | 2.89          | 2.89         | -3.6%     |
7. CONCLUSIONS

The theoretical background of the UPBD method for dual system has been highlighted. This method of design can accommodate both drift and performance level as the target design objectives. The method also gives member sizes in the beginning of design. The UPBD method has been applied to design of 12 numbers of dual system buildings of two plans and height categories of 8-, 10-, 12- and 15-storey heights and for various combinations of drifts and performance levels. The drifts and performance levels considered are: IO with 1% drift, LS with 2% drift and, CP with 3% drift. Layered shear wall shell elements have been used in modeling the shear wall. Displacement spectra corresponding to EC-8 design spectra for B type soil and seismicity level of 0.45g has been used. However, the design philosophy shall work at any other seismicity level. Default hinges of SAP2000 v.21 software for frame elements have been used as per ASCE-SEI 13. After the design for various target objectives, the buildings have been subjected to nonlinear pushover analysis and time history analysis under 5 spectrum compatible ground motions. The effectiveness of the UPBD method has been verified along both the directions of plan of the buildings considered. Fig. 11 and Fig. 12 along with Table 6 show that the target performance levels have been achieved in all cases. Fig. 13 and Table 7 show that the target drifts have been achieved to satisfactory tolerance limit. From the discussions on the results obtained, it is found that the UPBD method for dual system works well in satisfying target design objectives in terms of drift and performance level, under any specific hazard level. The advantage of the UPBD method lies in the fact that the target performance level and the target drift can be accommodated simultaneously in design and, member sizes are obtained at the beginning of design thus, avoiding iteration.

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Figures

(a) MDOF system (b) ESDOF system.

Figure 1

PQ-Curve for IO
RST-Curve for LS
UVW-Curve for CP
PQSTVW-Upper Limit
YZ-Lower Limit

Design Drift
Figure 2

Graphical representation of relation between ratio of length of wall and height of inflection with varying drift.

![Graphical representation of relation between ratio of length of wall and height of inflection with varying drift.](image)

Figure 3

Inflection height of 8 storey building considered in the study.
Figure 4

Displacement Spectra corresponding to EC-8 design spectra for soil type B at 0.45g level.

Figure 5

Shell component with connecting beams.
Figure 6
Shell element with multiple layers.

Figure 7
Moment rotation relation for RC plastic hinges (ASCE 41-13).
Figure 8

Building model considered in the study: (a) Plan I (b) Plan II (c) typical elevation [SW indicates shear wall].
Figure 9

Typical spectrum compatible ground motion: GM1.
Figure 10

Match of response spectra of SCGMs with EC-8 design spectrum.
Figure 11

Plastic hinges for typical building frames at end of time history analysis.
Figure 12

Pushover curves of typical buildings at the end of time history analysis.
Figure 13

IDR diagram of typical buildings.
Figure 14

Stress diagrams of layered shear wall for typical walls.
**Figure 15**

Moment-rotation diagram for typical layered shear wall model.