# Simplified Procedure for Displacement-based Design of Stepped Buildings

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**SUMMARY:**
This paper extends the applicability of direct displacement-based design (DBD) proposed by Priestley et al. (2007) to the design of stepped buildings. A series of stepped buildings, consisting of 4, 9 and 15 storeys, having steps in one direction, are designed as per the conventional force-based design method. Non-linear time history analyses are done using bi-directional excitation on 3-D models of the buildings. Two prevailing storey shear distribution patterns are compared with the time history analysis shear distribution to choose the appropriate one for stepped frames. A new distribution for base shear among orthogonal frames is proposed considering torsional effects. Accordingly, a simplified DBD procedure is proposed in this paper which can be applied to stepped frames and orthogonal frames independently. The most irregular among the selected buildings is designed as per the proposed method and the subsequent time history analysis shows good performance in terms of inter-storey drift.

*Keywords: Displacement-based design, stepped buildings, time history analysis, inter-storey drift*

## 1. GENERAL

Stepped buildings are recognized by several design codes as a typical form of vertical geometric irregularity that requires special design consideration. Such building forms are to be treated as vertically irregular when the lateral dimension of the maximum offset at the roof level exceeds 25% of the lateral dimension of the building at the base (IS 1893:2002). As per ASCE 7: 2005, when the horizontal dimension of the building in any storey is more than 130% of that in the adjacent storey, this building should be considered as vertically irregular. The codes recommend dynamic analysis for the design of this building category. Unlike regular buildings, in which the first mode participation is governing, there is a significant increase in the participation of higher modes, when vertical irregularities are introduced.

Based on an experimental study on set-back and stepped buildings, Wood (1992) concluded that the behaviour of stepped and set-back buildings is not much different from that of regular ones. But, Aranda (1984) found that the ductility demand for set-back buildings is more, in the storeys above the set-back level and hence needs special care while designing the top portions of the building. The analytical works of Sharooz and Moehle (1990) also agree with this observation and they found that there is more inter-storey drift damage in the tower-base junction. But, based on their experimental study on set-back buildings, they concluded that the fundamental mode dominates in the direction parallel to set-backs and hence static analysis is sufficient for set-back buildings.

Pinto and Costa (1995) evaluated the non-linear behaviour of set-back buildings of 4, 8 and 20-storeyed buildings. They observed a greater concentration of ductility demand in the lower storeys. However, some critical zones at intermediate heights were also observed. Wong and Tso (1994) discussed two issues: (i) whether the code based static shear is applicable to set-back buildings

(ii) whether higher mode period should be used in computing the base shear when the modal mass is more for a higher mode. They developed a modification factor for the fundamental time period for set-back buildings to solve the first issue and regarding the second issue, they realised that the base shear calculated based on higher mode period will give unnecessarily conservative designs.

As the fundamental period of the stepped building is different from that of stepped buildings, Sarkar et al. (2010) had proposed a correction factor ( $\kappa$ ) for the time period of regular building, given by

$$\kappa = \frac{T}{T_{ref}} = \left[1 - 2(1-\eta)(2\eta - 1)\right] \text{ for } 0.6 \le \eta \le 1.0 \qquad (1.1)$$

where $T$ is the fundamental period of stepped building, $T_{ref}$ is that of regular building and $\eta$ is the regularity index, which is calculated as the ratio of first mode participation factor for stepped building to regular building. This expression has been derived based on the modal analysis of 78 stepped frames with varying regularity indices, height and number of bays.

As vertically irregular buildings like stepped buildings are very common in India and are more vulnerable to earthquakes, this paper attempts to develop simplified DBD procedure for vertically irregular buildings, by suitably modifying the DBD principles which have been already established for regular buildings (Priestley, 2007), and focussing mainly on the load distribution patterns that give uniform damage among the yielding members.

## 2. EXAMPLE BUILDINGS SELECTED FOR THE STUDY

Ten buildings including regular and stepped buildings are considered. They are named as R4, S1-4, R9, S1-9, S2-9, S3-9, R15, S1-15, S2-15 and S3-15 where R denotes regular buildings and S denotes stepped buildings. The first number indicates the number of floor heights in a single step while second number refers to the maximum number of floors in the building. All the buildings have 4 bays of equal span (6m) at the base. The typical floor-to-floor height is 3.3m with the ground storey having a height of 4.5m. Steps have heights of 1, 2 and 3 floor heights, as shown in Fig. 2.1. Buildings are assumed to be located in medium soil with a design PGA of 0.6*g*.

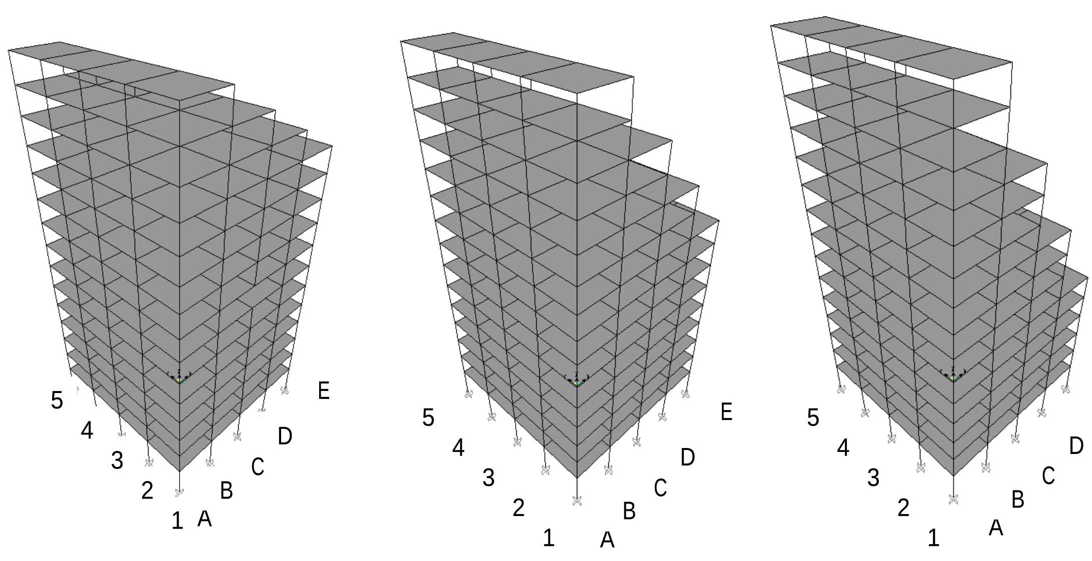


**Figure 2.1** 3-D models of stepped buildings with steps having 1, 2 and 3 floor heights

Buildings are modelled as 3-D frames in SAP 2000 NL and designed using the load combinations given in IS 1893:2002, with response spectrum analysis (RSA) for earthquake loading. Wind load is also taken as a load case in which basic wind speed is taken as 50m/s and terrain category 2 and structure class B as per IS 875 part 3 (1987) . In this paper, frames along the stepped direction are named as stepped frames and those along the perpendicular direction are named as orthogonal frames. Grid lines (1) to (5) are marked for stepped frames and (A) to (E) are marked for orthogonal frames.

## 3. TIME HISTORY ANALYSIS OF STEPPED BUILDINGS

Time history analysis (THA) was done using the program PERFORM 3D, with the non-linear properties calculated based on the structural design mentioned above. Beams are modelled using fibre elements and columns as lumped plasticity elements.

### 3.1. Selection of Ground Motions and their Scaling

Ten natural records were selected from PEER-NGA database and were made compatible with IS 1893:2002 spectrum for medium soil. Both the fault-normal and fault-parallel components were taken and the SRSS spectrum of each pair is generated. Scaling was done based on ASCE 7:05 such that the average of SRSS spectra of all ground motions does not fall below 1.3 times the corresponding ordinate of the design spectrum by more than 10% for the period range from 0.2*T* to 1.5*T*. The SRSS spectra of each pair of ground motions together with their average spectrum and 1.3 times the design spectrum are shown in Fig. 3.1.

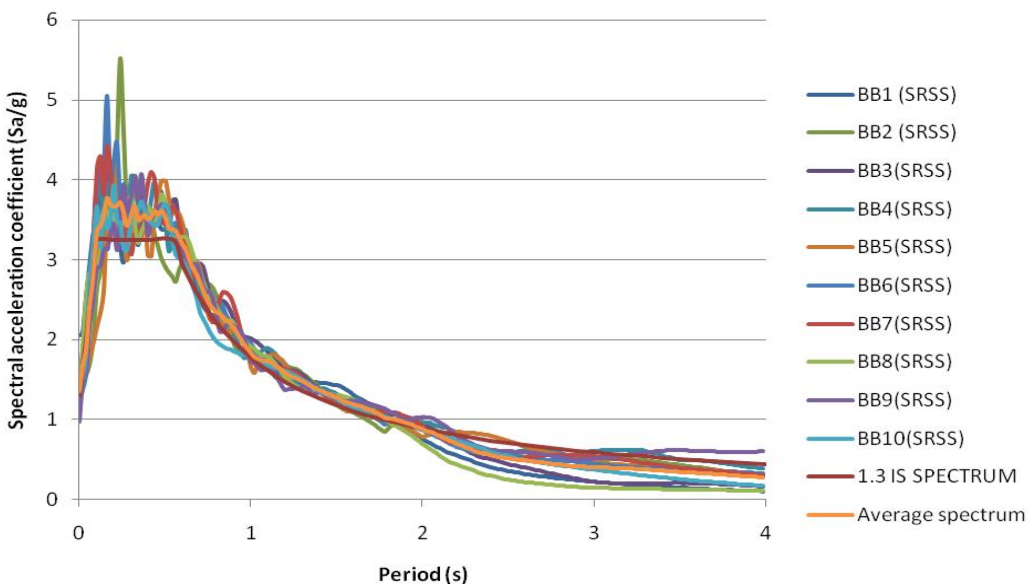


**Figure 3.1** Response spectra of selected time histories

Non-linear time history analyses results, in terms of base shear distribution in orthogonal frames and storey shear distribution in stepped frames, are presented in the following sub-sections.

### 3.2. Base Shear Distribution in Orthogonal Frames

The maximum base shear forces attracted by the orthogonal frames due to all the input ground motions were recorded and their average values are plotted and are shown in Fig. 3.2.

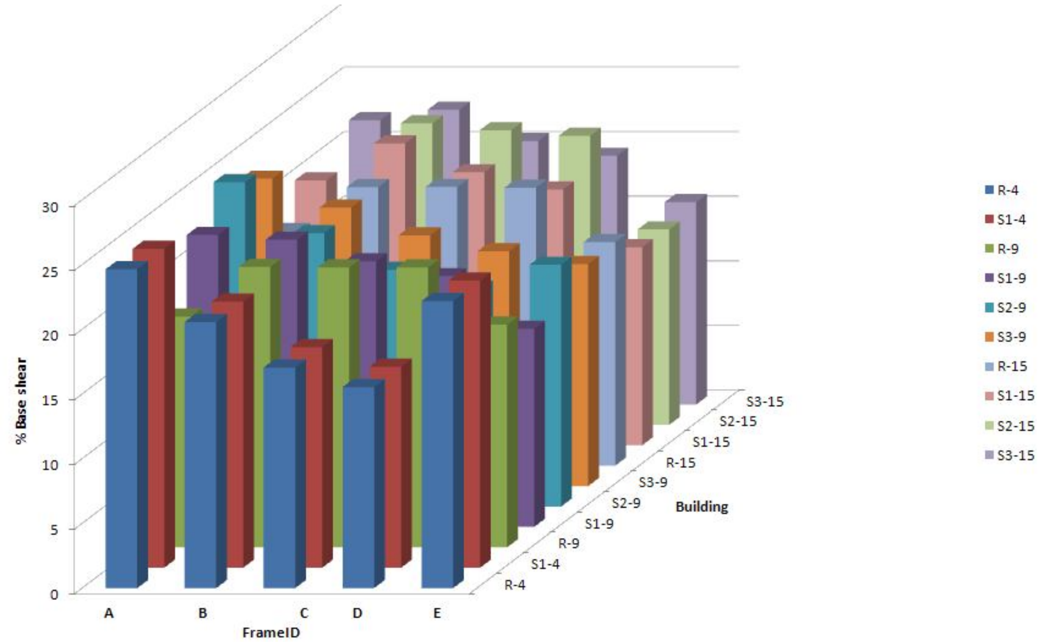


**Figure 3.2** Base shear distributions among orthogonal frames

It can be seen from Fig. 3.2 that, for stepped buildings, the percentage base shear attracted by frames on the flexible side is more compared to that on the rigid side, i.e., the base shear decreases in the stepping direction. This can be attributed to torsion, which causes more demand on the flexible side and to the reduced seismic weight near the stepped portion. It may be noted that the peak base shear values for each frame occurs at different instants of time.

A well-balanced design aims to have a similar level of inelastic action throughout the structure, which helps in avoiding premature local failures. This can be achieved if the orthogonal frames are designed as per the base shear distribution given by time history analysis. Based on the above results, an expression for base shear distribution among orthogonal frames is proposed in terms of $(n_s/n_f)$ where $n_s$ is the number of floor heights in one step and $n_f$ is the total number of floors.

$$V_k = qV_b' \tag{3.1}$$

where

$$q = \frac{0.2\dfrac{h_{av}}{h_k} + (k+0.5)^{2n_s/n_f}}{\sum_{k=1}^{n} 0.2\dfrac{h_{av}}{h_k} + (k+0.5)^{2n_s/n_f}} \tag{3.2}$$

Here $V_b'$ is the total base shear attracted by orthogonal frames and $k$ = 1, 2, 3…, starting from the stiff edge and increasing towards the flexible edge. $h_k$ is the height of the $k^{th}$ frame and $h_{av}$ is the average height of the orthogonal frames. In Eq 3.2, the first term takes care of increase in base shear due to increase in stiffness and the second term takes care of increase in base shear due to torsion which increases with increase in $k$ values. It gives equal base shear for all the frames when there is no stepping. The base shear distribution as per the proposed equation for S1-4, S3-9 and S3-15 are shown in Fig. 3.3, along with the time history analysis distribution.

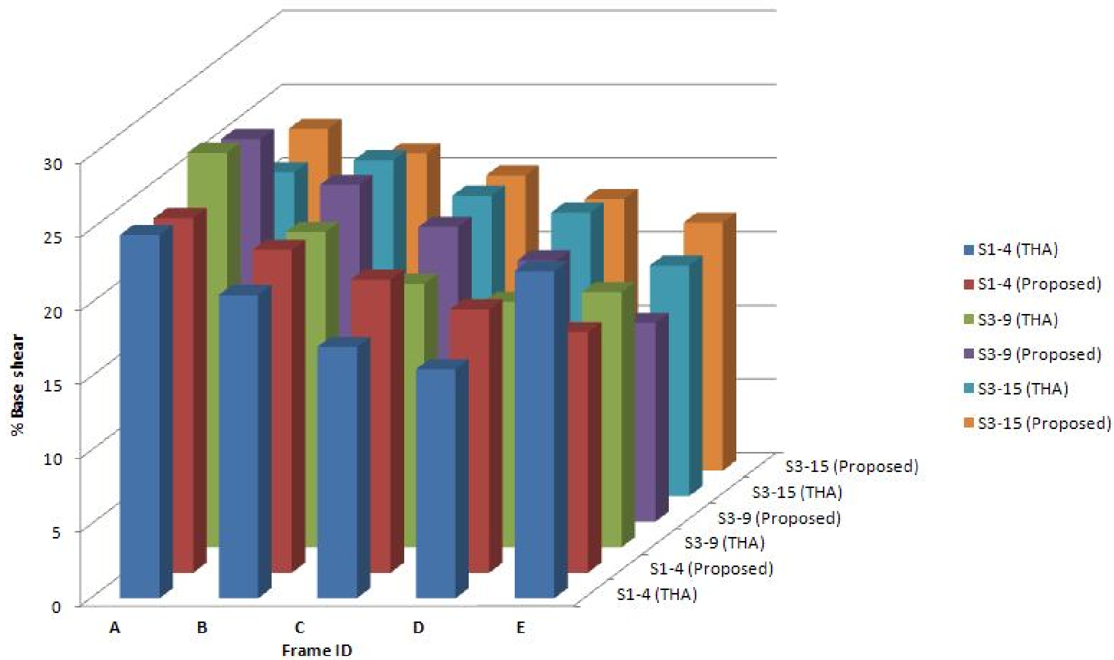


**Figure 3.3** Comparison of proposed base shear distributions with THA distribution

The proposed equation predicts the base shear conservatively for the frames on the flexible side; but the under-estimation of base shear on the stiff side is assumed to have little effect on the overall design. Hence, Eq. 3.1 gives a reasonable estimate of base shear distribution among orthogonal frames.

### 3.3 Storey Shear Distribution in Stepped Frames

As it is known that the behaviour of buildings in the non-linear range is influenced by the design storey shear distribution, two well known distributions (i) given by Priestley (2007) and (ii) given by Chao (2007), are selected for a comparison with the time history analysis shear.

As per Priestley (2007), the base shear ($V_b$) is distributed to various floor levels based in the inelastic displacement profile and the storey shear at any level can be written as,

$$V_i = 0.1V_b + 0.9V_b \frac{\sum_{j=i}^{n} m_j \Delta_j}{\sum_{j=1}^{n} m_j \Delta_j} \tag{3.3}$$

where $m_j$ is the seismic mass and $\Delta_j$ is the inelastic displacement at $j^{th}$ floor.

Chao (2007) conducted extensive non-linear time history analysis on a series of multi-storeyed frames and proposed the following storey shear distribution.

$$V_i = \left[ \frac{\sum_{j=i}^{n} w_j h_j}{\sum_{j=1}^{n} w_j h_j} \right]^{0.75T^{-0.2}} V_b \qquad (3.4)$$

where $w_j$ and $h_j$ are the seismic weight and height above the base of the $j^{th}$ floor and $T$ is the fundamental period calculated as per ASCE 7: 2005.

The two distributions, along with the time history analysis shear, are shown for buildings S1-4, S3-9 and S3-15 in Fig. 3.4. The fundamental time period of stepped buildings is calculated by modifying that of regular frames (determined as per ASCE7: 2005) using Eq. 1.1. The modified fundamental period and the appropriate seismic weight at each floor of the stepped building are used in Eq. 3.3 to find out the shear distribution for the stepped buildings.

It is clear from Fig. 3.4 that, the Chao distribution (2007) conservatively estimates the storey shear for all the frames except at the top floor of 4-storeyed frames. But, when the load distribution as per Priestley (2007) is used, it under-estimates the storey shear near the top of the building where higher mode effects and variations due to stepping effects are predominant. Hence, it can be concluded that for buildings stepped in one direction, Chao distribution can be adopted conservatively, when used with proper fundamental period of stepped building and the seismic mass at various floor levels.

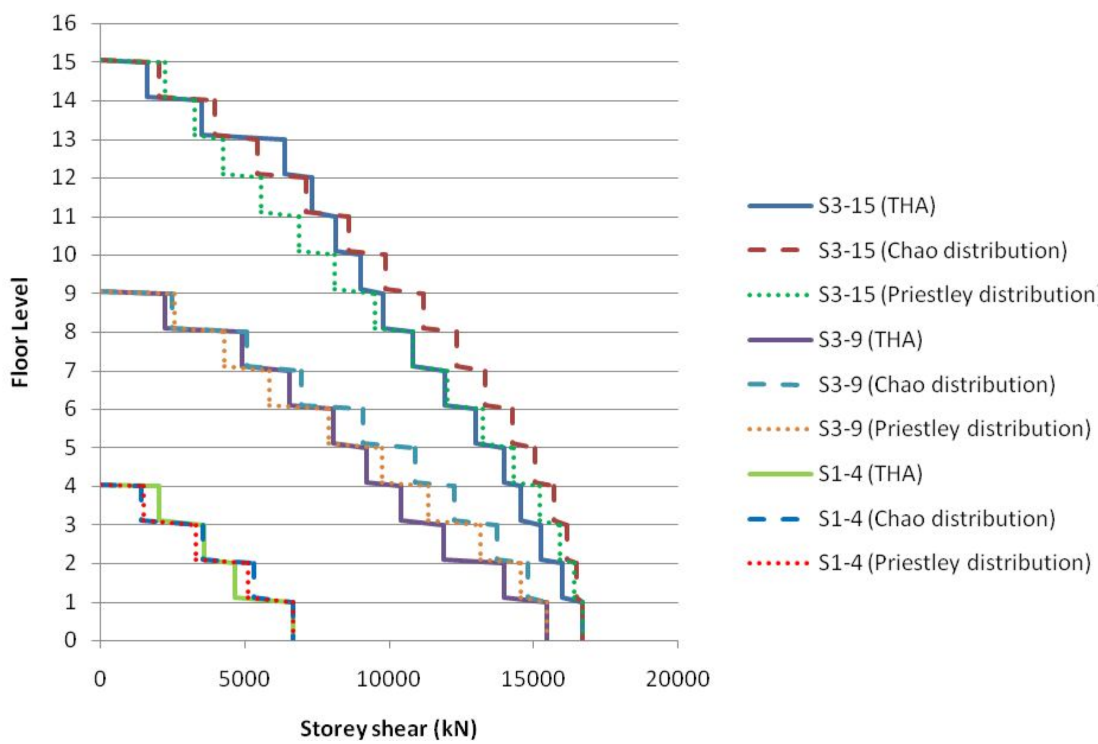


**Figure 3.4** Shear distributions in stepped frames

## 4. DESIGN OF STEPPED BUILDINGS USING SIMPLIFIED DBD OF 2-D FRAMES

The data obtained for stepped as well as orthogonal frames is used for developing a simplified procedure for DBD of stepped buildings. As the regularity index of building S3-9 is found to be the least among the considered frames, it is selected for re-design using simplified DBD procedure. Stepped frames are designed as per the load distribution of Chao et al. (2007) with appropriate masses at vaious floors. Base shear attracted by orthogonal frames are calcuated for an equivalent frame having number of floors equal to maximum number of floors (that of flexible side) and the respective total floor masses lumped at various floor levels. This happens to be the same stepped frame which is considered in the x-direction, thus reducing the design efforts. The total base shear in the orthogonal direction is distributed among the frames using Eq. 3.1.

### 4.1 Performance Evaluation of Re-designed S3-9 Building

As inter-storey drift is directly related to structural damage, it is taken as the parameter for performance evaluation. The inter-storey drift obtained for S3-9, which is designed by code-specified method (RSA) and by the proposed DBD are shown in Fig.4.1. Even though the drifts of the building designed by the proposed DBD match well with that of the building designed as per RSA in the bottom two-third portion of the building, it is found to exceed the permissible limit in the top 3 storeys. This shows the need for further modification of the design procedure.

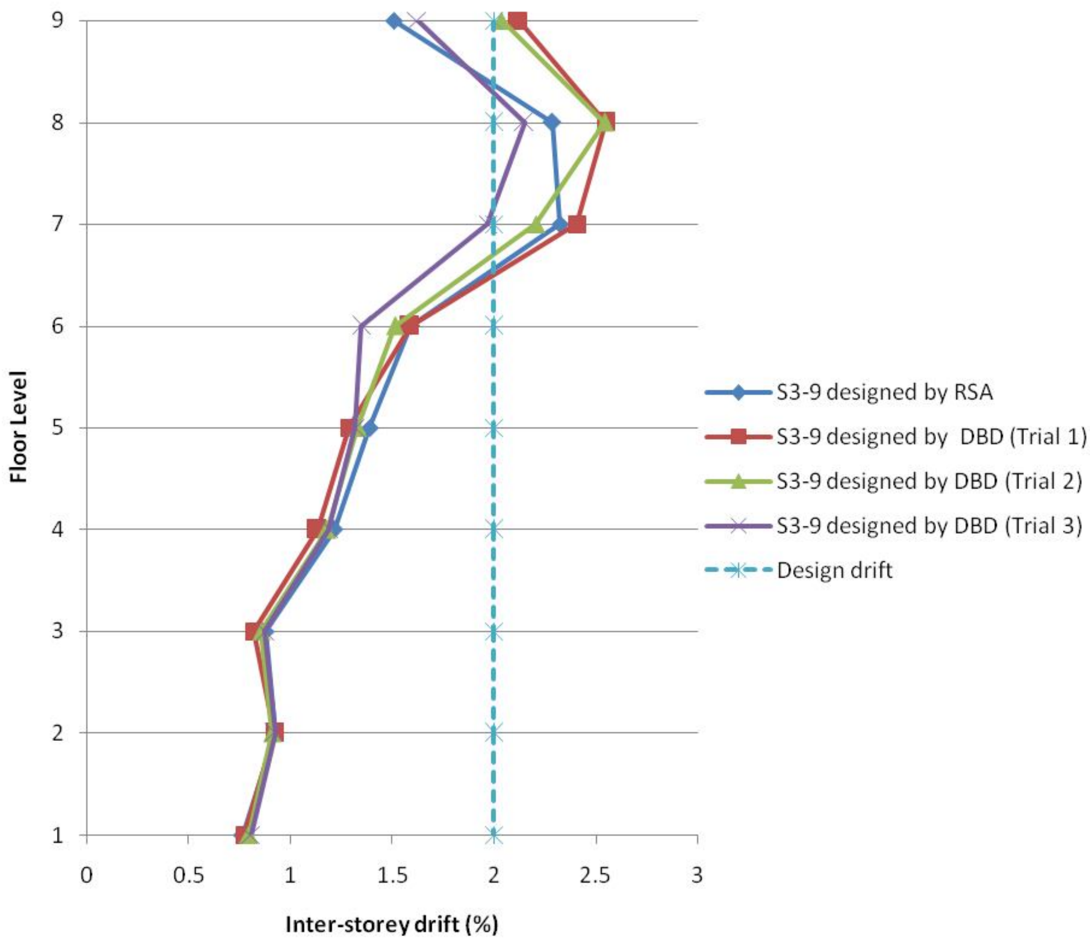


**Figure 4.1** Inter-storey drift for stepped frames

In an attempt to increase the design forces for top storey members, the load distribution is done as per the same distribution (Chao, 2007), with the only difference that $W_i$ is replaced with $W_i$*, which is the seismic weight of the $i^{th}$ floor of a regular building without steps. Accordingly, the building is re-designed and the inter-storey drift is calculated. As evident from Fig. 4.1, this second trial also is not much effective in reducing top storey drift.

Hence, it is decided to design the stepped frames for a higher base shear, which is the same as that of the regular building, keeping the base shear for orthogonal direction same as that of stepped building and the load distribution as that of regular building. Non-linear time history analysis of this frame (designed as per Trial 3) showed an almost uniform damage along the height and the inter-storey drift of all storeys within the allowable limit, say, 2.0% (except for a slight increase for the 8$^{th}$ storey). It is inadvisable to go for uniform damage beyond this limit and the best solution is to limit the damage within permissible limits at all levels. On the whole, the performance of the proposed DBD is better than that of the code-specified RSA. Hence, DBD using Trial 3 is adopted as the final design method for stepped building.

Inter-storey drifts of orthogonal frames are also plotted to see the torsional effects. It is clear from Fig. 4.2 that the drift is almost uniformly distributed for all the frames and is within the allowable limit. Drift at a particular level, increases towards the flexible edge which agrees with the force response (i.e. base shear is more for flexible edge).

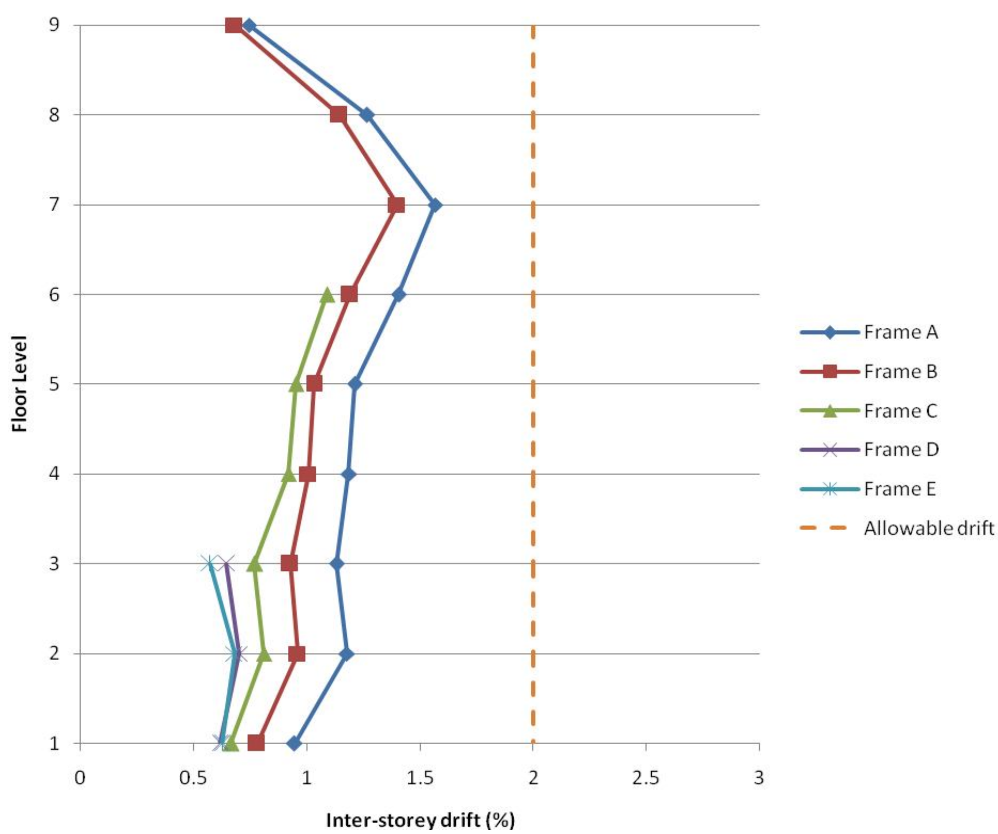


**Figure 4.2** Inter-storey drift of orthogonal frames (average of ten responses)

A flow chart for the proposed simplified DBD procedure is shown in Fig.4.3, which includes the design of frames in both the directions and are based on the detailed time history analyses of 3-D models of stepped buildings. Same detailing can be followed for beams in a particular storey, even though the superimposed load on the stepped portion is different from that of the other potions. Similarly, columns near the stepped portion can be treated as inner columns as they will attract more forces due to stepping.

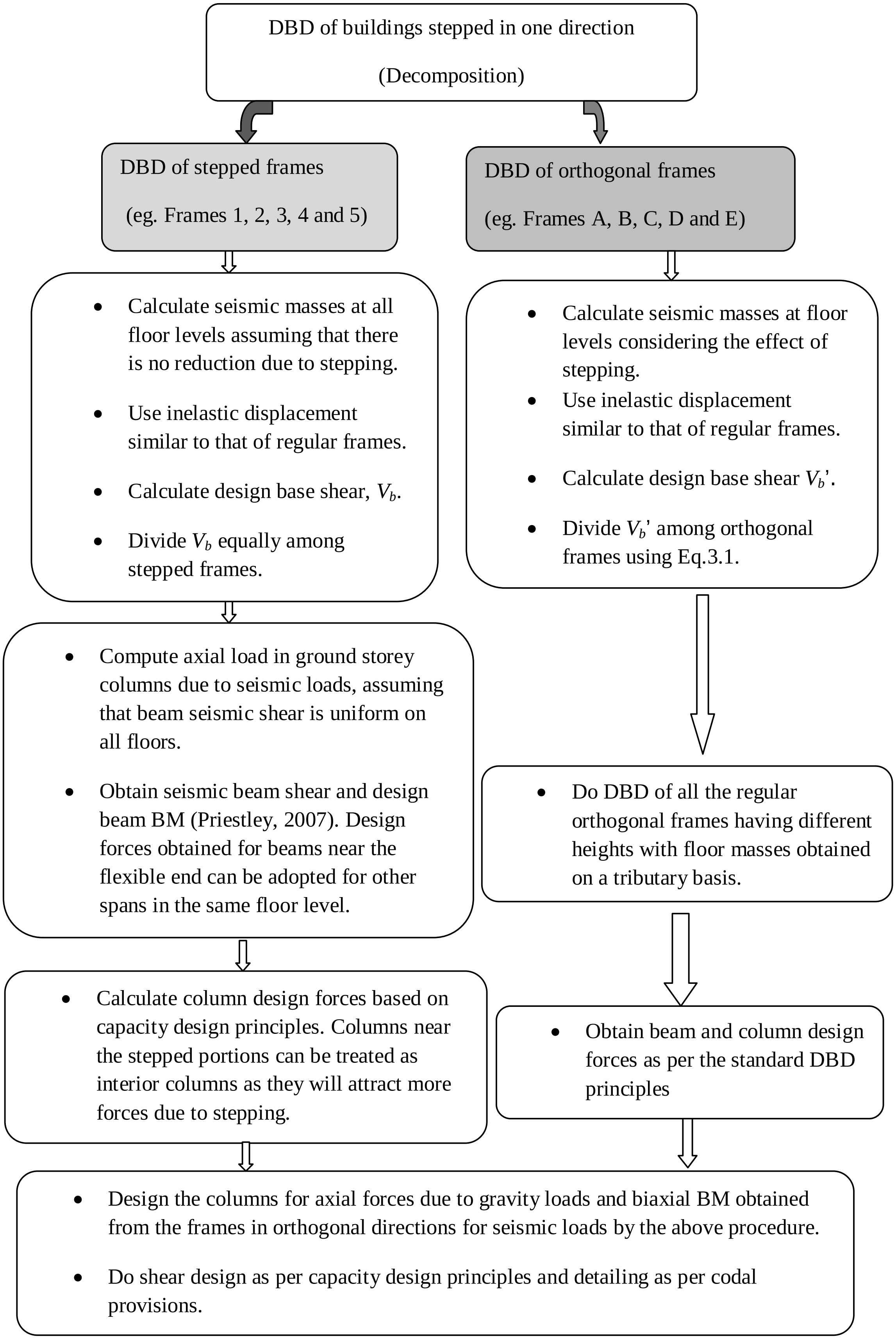


**Figure 4.3** Flow chart for simplified DBD of stepped buildings

## 5. SUMMARY AND CONCLUSION

Non-linear time history analysis results of three regular buildings and seven stepped buildings, designed as per the response spectrum analysis (IS 1893:2002), and subjected to two-component earthquake excitations, are used to derive a simplified DBD procedure for stepped buildings. It is found that the flexible side attracts higher base shear force compared to the stiffer side, cautioning the designer to take special care while designing the orthogonal frames. This effect is due to the torsional rotation developed due to differential lateral displacements between the taller and shorter sides of the building and also due to lesser seismic weight near the shorter edge.

The procedure for DBD of stepped buildings is proposed in such a manner that the design of stepped frames and orthogonal frames can be done separately, and hence the designer needs to analyse only planar 2-D frames. Higher mode effects are predominant in stepped buildings and to reduce this undesirable effect, suitable modifications are made in the design procedure after performing several analyses, designs and verifications.

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