DISPLACEMENT BASED DESIGN OF WALL-FRAME AND SHEAR WALL BUILDINGS

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Displacement Based Design of Wall-Frame and Shear Wall Buildings

Major Project

Submitted in partial fulfillment of the requirements for the Degree of

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(Computer Aided Structural Analysis And Design)

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Declaration

This is to certify that

i) The thesis comprises my original work towards the Degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis and Design) at Nirma University and has not been submitted elsewhere for a degree.

ii) Due acknowledgement has been made in the text to all other material used.

Mehboob H. Jindani

Certificate

This is to certify that the Major Project entitled **"Displacement Based Design of Wall-Frame and Shear Wall Buildings"** submitted by **Mr. Mehboob H. Jindani (Roll No: 12MCLC12)** towards the partial fulfillment of the requirement for the Degree of Master of Technology in Civil Engineering (Computer Aided Structural Analysis And Design) of Nirma University, Ahmedabad is the record of work carried out by him under our guidance and supervision. In our opinion, the work submitted has reached a level required for being accepted for examination. The results embodied in this major project work to the best of our knowledge have not been submitted to any other University or Institution for award of any degree or diploma.

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Abstract

The traditional Force Based Design (FBD) given in Seismic code uses empirical approach without giving due consideration to the displacements which are actually responsible for the damage. After the yield point, the strength has least role to play, whereas the failure will take place at an ultimate displacement depending upon the level of ductility present in the structure. Therefore, it seems rational to carry out a seismic design wherein displacements are considered at the start of the design process. In order to prevent collapse in a major earthquake, the ductility demand on the structural elements and the overall deformation of the structure needs to be controlled. It is suggested in various research articles that this can be achieved more rationally with Displacement Based Design (DBD) rather than FBD.

In the present study, traditional FBD approach given in IS 1893 (Part 1) : 2002 is reviewed and its limitations are discussed. DBD is firstly implemented to single storey building modeled as Single Degree of Freedom (SDOF) system. Comparison among FBD and DBD of single storey building shows that later provides double the base shear, higher time period, lower stiffness and ductility. Later on, DBD is implemented to two buildings with different structural systems, namely, Wall-Frame and Shear Wall. Shear wall building is analyzed using DBD. Like in the case of SDOF system, DBD provides higher baser shear as compared to FBD, however, ductility reduces substantially. A parametric study is carried for shear wall building with respect to the height of the building.

Similarly, Wall-Frame building is analyzed and base shear contribution of Wall and Frame is derived. It is designed using DBD and found that Time period, Damping and Base Shear of the building is higher as compared to FBD, however ductility is lower. A parametric study with respect to base shear contribution of wall and frame is carried out.

Apart, Inelastic Design spectrum is developed from design spectrum given in IS 1893 (Part 1) : 2002. A four Storey Reinforced Concrete Frame building is considered to implement DBD using Inelastic Design Spectrum. It is found that the Response reduction factor for Inelastic spectrum comes out to be low as compared to Elastic spectrum for FBD.

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Abbreviations, Notations and Nomenclature

DBD .... Displacement Based Design

A_h .... Design Horizontal Seismic Co-efficient

SDOF .... Single-Degree of Freedom System

MDOF .... Multi-Degree of Freedom System

R.C. .... Reinforced Concrete

R.C.C. .... Reinforced Cement Concrete

l_w .... Width of shear wall

Δ_u .... Design displacement

Δ_y .... Yield displacement

ϕ_u .... Ultimate curvature

ϕ_y .... Yield curvature

V_B .... Base shear

Z .... Zone factor

I .... Importance Factor

R .... Response Reduction factor

T .... Time period

ω .... Natural frequency

m.f. .... Modification Factor for Damping

S_a .... Spectral Acceleration

V_F .... Base Shear carried by Frame

V_W .... Base Shear carried by Wall

β_F .... Base shear ratio of frame to total

n .... No. of storeys

H_e .... Effective height of SDOF System

H_{CF} .... Wall Contraflexure height

ε_y .... Yield strain of Reinforcement

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Chapter 1

Introduction

1.1 General

The seismic design in all current codes and standards has been based on Forces (i.e Acceleration) rather than Displacements. The reason being that in past history, very few structures were specifically designed for seismic actions.

But after several major earthquakes (Japan: 1925 Kanto Earthquake, USA: 1933 Long Beach Earthquake, New Zealand: 1932 Napier Earthquake) that occurred in 1920's and early 1930's, it came to notice that the structures which were designed for wind forces performed better than those without specific lateral force design. As a result the importance of lateral force design was realised and the design codes started including seismic design for the structures in high seismic zones. Earlier, approximately 10% of the building weight, regardless of building period was distributed and applied vertically along the height of building.

Earthquake induces forces and displacements in the structures. These forces and displacements, for an elastic system are directly related to stiffness of the system. But, for the structures responding in- elastically, the relationship is not that straightforward as it is dependent on both the current displacement and the history of displacement during the seismic response.

For a while, it has been understood that strength has a lesser importance when considering seismic actions. In the regular design method, the structure is designed for lesser earthquake forces. This is due to the consideration of factors like ductility, over strength, redundancy etc. The structure is capable of deforming inelastically and the deformations imposed by earthquake are such that there is no complete collapse of structure. This implies damage but not collapse. Since design level earthquakes are by definition rare events, with a typical annual probability of occurrence (or exceedence) of about 0.002, we accept the possibility of damage under the design earthquake as economically acceptable, thus drawing benefit of economy.

The most common building form is reinforced concrete frame structures. Apart from them, there may be several types of structures in a seismically active region. Due to variability in geometric shapes, material properties, structural parameters like section shapes and orientations, the response of these structures to earthquake loads becomes difficult.

It has now been understood and slowly being accepted, that the damage is more related to relative displacements than to forces. Hence, one of the alternatives of the methodologies based on displacement is "Displacement Based Design (DBD)" proposed by Priestley[4].

The concept of Displacement based design was introduced in 1990's. It is considered to be a more logical and rational alternative to the traditional Force based Design (FBD). In this method, the displacement is considered as the primary response variable of structures which means that, design or acceptance criteria and capacity-demand comparisons are expressed in terms of displacements rather than forces. The stiffness and time period are the response quantities rather than input quantities. The building is pushed to the allowable displacement limits and the actual ductility is determined.

1.2 Objective Of Study

Following are the objectives of the present study:

I) To study the shortcomings of FBD and to understand the procedure to carry out DBD.

II) To study and carry out displacement based design for Wall-Frame and Shear Wall building using Elastic design spectra.

III) Development of Constant ductility based Inelastic Design Spectra using Newmark-Hall procedure.

IV) Comparison among the use of elastic and inelastic design spectra.

1.3 Scope of the Work

The scope of the present study comprises of:

I) Understanding DBD and its comparison to FBD.

II) Implementation of DBD for a Single storey building modelled as SDOF system.

III) Study of methods to carry out the displacement based design of the wall-frame and shear wall buildings.

IV) Application of DBD to Wall-Frame Building and Shear Wall Building.

V) Comparison of response quantities between FBD and DBD.

VI) Developing Inelastic Design Spectra from the IS 1893 : 2002 based Elastic Design Spectra.

VII) Use of Inelastic Spectra for an RC Frame building.

1.4 Organization of Report

The content of report is divided into seven chapters as follows:

Chapter 2 discusses the literature review. In this chapter literature regarding displacement-based design and its implementation on various buildings are briefly discussed.

Chapter 3 presents the implementation of DBD. It includes procedure of FBD, comparison of FBD and DBD, basic formulation of DBD and its advantages are explained using an illustrative example of SDOF system.

Chapter 4 presents displacement based design of Shear Wall building and its comparison with FBD. For Shear wall buidings, two building heights

Chapter 5 discusses the Displacement Based Design of Wall-Frame building. Different values of wall-frame base shear contributions have been

Chapter 6 focusses on the development of constant ductility based Inelastic Spectrum and its application to a RC Frame building.

Chapter 7 summarizes the work done in the major project. It consists of summary of work done, conclusions derived from the current study and future scope of work.

Chapter 2

Literature Review

2.1 General

Present chapter is focussed towards literature study pertaining to the theory of DBD, its implementation and parameters related to it. Literature that includes books, guidelines and journal papers are studied to understand the concept of DBD and its application to different types of structures such as simple RC frame, Wall-frame and shear wall structures. Also literature pertaining to development of inelastic spectra is studied. The basic principles of DBD that are used in most of the available literature include inelastic first mode response, use of substitute structure approach, calculating system damping based on ductility. Thus, the deformations (drift or displacement) of the structure are the starting point of the design and not the end product as in the traditional force-based design method. The end-product of the design is stiffness, time period.

Various literatures related to displacement-based seismic design of R.C. structures studied are briefly mentioned below.

2.2 Implementation of Displacement Based Design on Buildings

2.2.1 Basic of Displacement Based Design

Medhekar and Kennedy[1] reviewed the conceptual basis of the spectral acceleration-based design method currently used in seismic codes and its limitations are also discussed. The objectives of this paper are : (a) to present the theoretical basis of the displacement based design method, and (b) to show how this method is applied, as may be used for the serviceability limit state and the ultimate limit states, to the design of buildings modelled as multi-degree-of-freedom systems. Basics of substitute-structure approach for DBD of MDOF systems are also discussed.

Lin et al.[11] proposed a linear iteration method using Substitute Structure approach, where target displacement is specified and the required design force, member strength and stiffness are obtained. The procedure has been developed for MDOF systems. In this paper, the strong-column-and-weak-beam design criteria are adopted to design the structural members. The iterations are discontinued when the end moment of each member is equal or approximately equal to its yield moment. It is concluded that by using the substitute-structure approach, the ultimate displacement of buildings can be well estimated by the displacement-based design procedure. The drift ratio influences the yield displacement, ductility, equivalent damping and the fundamental period of the designed building.

Priestley et al [4] discussed the shortcomings with current force-based design, seismic input for displacement-based design , fundamentals of direct displacement-based design, and analytical tools appropriate for displacement-based design. The DBD procedure to design a new structure as well as for evaluation of existing structures is also given. The design procedure developed is based on a secant-stiffness (rather than initial stiffness) representation of structural response, using a level of damping equivalent to the combined effects of elastic and hysteretic damping. The design method is extremely simple to apply, and very successful in providing dependable and predictable seismic response. The theory and application of DBD is explained to all kinds of structures such as bridges, shear wall buildings, wall-frame buildings, etc.

Park and Paulay[2] described useful information on ultimate deformation and ductility of members with flexure. Theoretical moment-curvature determination, ductility of unconfined beam sections, ductility of unconfined column sections, compressive stress block parameters for concrete confined by rectangular hoops and theoretical moment-curvature curves for sections with confined concrete are discussed in detail.

Shibata and Sozen [5] formulated the substitute-structure method. It is a method of representing a mlti-degree of freedom structure to a single degree of freedom structure. The substitute-structure method is a procedure for determining the design forces, corresponding to a given type and intensity of earthquake motion represented by the design spectrum, for a reinforced concrete MDOF structure. The method is explicitly a design (and not an analysis) procedure. The central and significant feature of the substitute-structure method is that it provides a simple vehicle for taking account of inelastic response of reinforced concrete in the design of multi-degree-of-freedom structures.

2.2.2 Wall Frame Buildings

Priestley et al [4] The concept of DBD for Wall-frame buildings is explained, the distribution of base shear force to wall and frame is also discussed. The related equations for yield displacement, design displacement, hysteresis damping, substitute structure approach and height of contraflexure are defined. The drift amplification factor for higher mode effects is also specified.

Yavas [12] investigated the displacement profile for wall-frame type structures to be used in the DBD of Dual Frame. An iterative two phase method that uses DBD in the first phase and nonlinear time history analysis in the second phase is proposed for determining the displacement profiles. Displacement profiles for six, eight and twelve story four span dual-frame type structures are determined. The effect of the number of bays and the base shear ratio carried by the wall are also investigated. A new displacement profile function is proposed for the DBD of dual frames.cThe equation for deriving the equivalent damping that is the sum of elastic and hysteresis damping for the wall-frame is given. It is concluded that DBD procedures developed for the moment resisting frames can be used for the design of wall frame structures. It is found that the number of bays and the base shear ratio carried by the wall do not change the displacement profile. A new displacement profile function is also proposed.

2.2.3 Shear Wall Buildings

Priestley et al [4] : The procedure for performing DBD on a shear wall building is explained. The equations for computing yield and design displacement is given. The response of shear wall buildings in torsion is explained and modifications to the DBD method is explained. The DBD procedure for the buildings having unequal wall lengths is explained. The effect of flexibility of foundations is also discussed.

Urrego and Bonett [17] has presented a procedure for displacement-based design. The method assumes a geometrical section of known flexural reinforcement at the critical section. The moment capacity is obtained by equilibrium of the section using concrete and reinforcing steel properties and axial forces. The design spectrum in ADSR format is used to determine the ductility demand and it is compared with the capacity of the structure. Thus, it is possible to define whether is necessary to change the initial reinforcement proposed until structural capacity is equal or bigger than the seismic demand. When this iterative procedure concludes, the section is satisfactorily designed because the analysis, as well as the design, are made simultaneously. Finally, the maximum displacement and curvature ductility are calculated. The method has been applied to a 15-storey cantilever structural wall building. The results indicate that the procedure is able to satisfy the design objectives and fulfill a non-linear deformation pattern.

Rad and Adebar [10] discussed the influence of flexural yielding at multiple locations over the wall height and influence of shear deformations due to diagonal cracking of the wall. It is concluded that flexural yielding of the wall at numerous locations over the height reduces the maximum shear force in the wall. it is also shown that the reduced shear stiffness due to diagonal cracking further reduces the maximum shear force at the base of the wall.

2.3 Development of Inelastic Spectra

Chopra and Goel [13] described the procedure to develop well known constant ductility design spectrum (Inelastic spectrum) and illustrated by examples. The definition and concept of inelastic spectrum is shown and its formulation is also discussed. The procedure followed is from "Earthquake Spectra and Design" by N.M. Newmark and W. J. Hall (1982) to convert Elastic Spectra to Inelastic Design Spectra.

Chopra and Goel [6] has developed an equally simple method as to use of elastic design spectra that is based on the well-known concepts of inelastic design spectra. The existing procedure using elastic design spectra for equivalent linear systems is shown to underestimate significantly the displacement and ductility demands. Conclusion: It is demonstrated in this paper that the procedure provides: (i) accurate values of displacement and ductility demands. The existing procedure, i.e. using elastic design spectra is shown to be deficient in yet another sense; the plastic rotation demand on structures designed by this procedure may exceed the acceptable value of the plastic rotation, leaving an erroneous impression that the allowable plastic rotation constraint has been satisfied.

Newmark and Hall [14], in the monograph, gives the method for the development of response spectra from the recorded ground motions. Normalization factor for the conversion of response spectra to design spectra is given. It also provides the detailed procedure of construction of a design spectrum. Also, it gives the R-μ-T_n relationship, that is required for the conversion of elastic spectrum to inelastic spectrum.

2.4 Summary

In this chapter, review of relevant literature is carried out. The review of literature includes the development of displacement-based design method, and implementation of this method to SDOF and MDOF systems. It also includes the advantages and limitation of the DBD. This review helps to develop basic understanding of DBD and its application to various structures.

Chapter 3

Displacement Based Design Implementation

3.1 Introduction

Before discussing about the implementation of Displacement Based Design and its components, it is important to first of all, to discuss the basic steps of Force Based Design and its shortcomings and drawbacks.

The present chapter focusses on the basic understanding of the DBD and its application to SDOF system with an illustrative problem of a SDOF system. This type of SDOF problem has already been worked out in the institute by Palak K. Thacker (09MCL021) for the major project titled "Displacement Based Design of RCC buildings". It is done in the present work for the smooth flow of understanding.

3.2 Force Based Design

Force Based design is currently being used all over the world in many countries seismic design codes. Although current force-based design (spectral acceleration-based design) is considerably improved compared with procedures used in earlier years, there are many fundamental problems with the procedure, particularly when applied to reinforced concrete structures. In order to examine these problems, it is first necessary to briefly review the force-based design procedure, as currently specified by IS 1893 (Part 1): 2002.

3.2.1 Procedure of Force-Based Design

The step-by-step procedure of FBD as per IS 1893 (Part 1): 2002 is summarized as follows:

Step I) Assume structural dimensions and calculate the seismic weight of the building (W_e).

Step II) Calculate the time period in both the horizontal direction using the Equation (3.1) and (3.2) given in the code.

For RC frame building without infill panels,

$$T = 0.075 \times h^{0.75} \tag{3.1}$$

For all other buildings with brick infill panels,

$$T = 0.09 \times \frac{h}{\sqrt{d}} \tag{3.2}$$

Where h = height of the building, and d = Base dimension of the building along the considered direction of lateral force

Step III) Select the zone factor based on the Select Zone factor (Z), Importance factor (I), Response reduction factor (R) and Damping percentage (5% for concrete and 2% for Steel) .

Here, Z depends on seismic activities estimation in various regions of country. Importance factor defined based on implementation of structure under consideration. R is a function of parameters like over strength and ductility of material. Damping coefficient depends on type of structure.

Step IV) Select the type of the soil based on site conditions viz. hard, medium or soft.

Step V) Calculate the Spectral acceleration coefficient (S_a/g) from Design Response Spectra given in the code, shown in Figure 3.1 below.

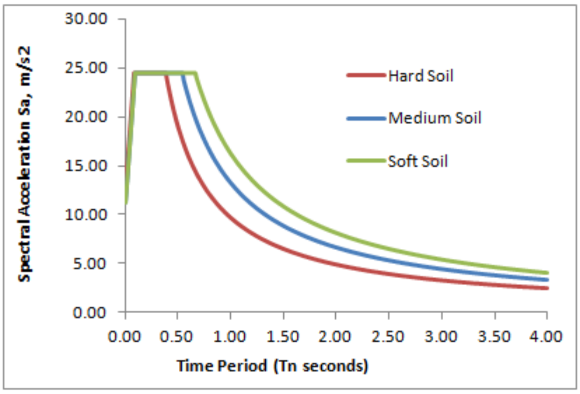

Figure 3.1: IS Design Acceleration Spectrum

Step VI) Calculate the Static Base shear from the following Equation (3.3):

$$V_B = Z/2 \times I/R \times S_a/g \times W_e \times m.f. \tag{3.3}$$

Where Z = Zone Factor I =Importance factor S_a/g = Spectral acceleration co-efficient W_e = Seismic Weight of the structure m.f. = Modification factor for damping as per Table 3 IS 1893: 2002

Step VII) Estimate member elastic stiffness based on preliminary estimates of member size.

Step VIII) Based on the assumed member stiffness, dynamic analysis can be performed either by Time History Method or by the Response Spectrum

Method.

Step IX) However, in either method of dynamic analysis, the design base shear $V_{B,DYN}$ shall be compared with a base shear $V_{B,STAT}$ calculated as given in former steps. When $V_{B,DYN}$ is less than $V_{B,STAT}$, all the response quantities like member forces, displacements, storey forces, storey shears and base reactions shall be multiplied by $V_{B,STAT}$ / $V_{B,DYN}$.

Step X) Distribute the deign Base Shear (VB) along the height of the building as per following Equation (3.4):

$$Q_i = V_B \times \frac{W_i \times h_i^2}{\sum_{j=1}^{n} W_j \times h_j^2} \tag{3.4}$$

where

Q_i = Design lateral force at floor i,

W_i = Seismic Weight of floor i,

h_i = Height of floor i measured from base, and

n = Number of levels at which the masses are located.

Step XI) Analyze structure under seismic force.

Step XII) Check the Displacement.

3.3 Displacement Based Design

In the Displacement Based Design (DBD) procedure, the seismic design is carried out by specifying a target displacement. Strength and stiffness are not the design variables in the procedure; instead they are the end-products. Displacement-based design is a seismic design methodology that uses displacements as the basis for the design procedure. In DBD procedure, seismic design is performed by specifying a target displacement rather than a displacement limit. Strength and stiffness are not variables in the procedure, but they are the end results.

In this section, some light is thrown on the displacement based design of structures. It will be understood more clearly when an SDOF problem is solved in the subsequent section:

i) First of all if the structure is MDOF then it is first converted to equivalent SDOF system using the Substitute-structure approach as the DBD method is primarily based on the inelastic first mode of vibration.

ii) The final drift is to be reduced to include the higher mode effects using the Drift Amplification Factor.

iii) The yield displacements and design displacements is estimated using the pre-defined equations based on the yield and ultimate curvature.

iv) Based on the yield and ultimate displacements, ductility is found out and then based on that, hysteresis damping is calculated.

v) The code based acceleration spectrum is converted to displacement spectrum, as shown in Figure 3.2 below.

vi) Based on the damping ratio and the design displacement, time period is found from the spectrum.

vii) Then stiffness is found out from the effective mass and time period.

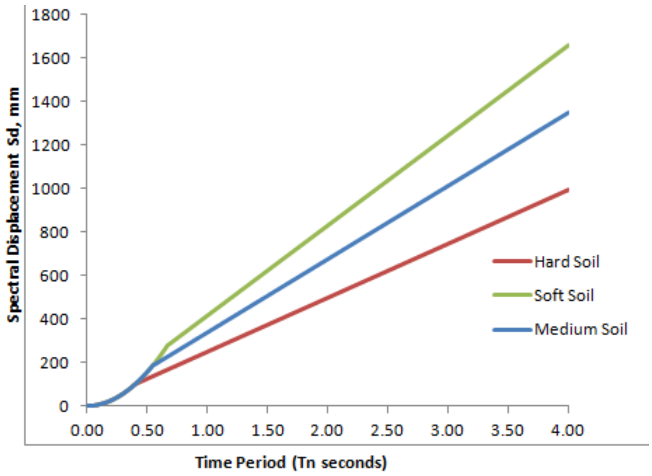

Figure 3.2: IS Design Displacement Spectrum

viii) The base shear is the product of the stiffness calculated and the design displacements.

ix) The base shear is then distributed across the height in a triangular profile as per the below given Equation (3.5):

$$Q_i = V_B \times \frac{W_i \times h_i}{\sum_{j=1}^{n} W_j \times h_j} \tag{3.5}$$

3.3.1 Principles of DBD

Damage in the structure can be easily related to deformations rather than strength. Displacement-based Design (DBD) has been developed in order to remove the deficiencies of widely used code based spectral acceleration design methodology. The method is based on displacement, which can be easily obtained being a basic quantity. DBD defines the structure under consideration as a single degree of freedom (SDOF) system and considers its performance at peak displacement response, instead of its initial elastic characteristics. This is realized by Substitute-Structure Approach. The Substitute-Structure Approach is a procedure where an inelastic MDOF system is modelled as an equivalent elastic SDOF system, and is termed as the Substitute-Structure.

In Figure 3.3 (a), it is represented how an MDOF system can be converted to an equivalent SDOF system. The bi-linear envelope of the lateral force- displacement response of the SDOF representation is shown in Figure 3.3(b). An initial elastic stiffness is denoted by Ki and post yield stiffness by rKi. DBD characterizes the structure by secant stiffness (Ke) at maximum displacement (Figure 3.3(b)). The damping considered for the system is an equivalent viscous damping, which consists of combined elastic damping given in the code viz. 2% for steel and 5% for concrete, and the hysteretic energy absorbed during inelastic response.

Thus, for a given level of ductility demand, the equivalent system damping can be obtained from Figure 3.3(c). Since the effective properties of the substitute-structure are elastic, a set of elastic displacement response spectra given in seismic codes can be used for design. Therefore, the substitute structure-approach allows an inelastic system to be designed and analyzed using elastic displacement response spectra.

The effective time period (Te) at maximum displacement response can be obtained from a set of displacement spectra for different damping levels as shown in Figure 3.3(d), for a calculated design displacement corresponding damping estimates. The effective stiffness Ke of the equivalent SDOF system at maximum displacement can be given by,

$$K_e = 4\pi/T_e^2 \times m_e \tag{3.6}$$

The design base shear is obtained by,

$$V_B = K_e \times \Delta_d \tag{3.7}$$

where,

K_e = Effective stiffness of the system.

T_e = Effective time period of the system,

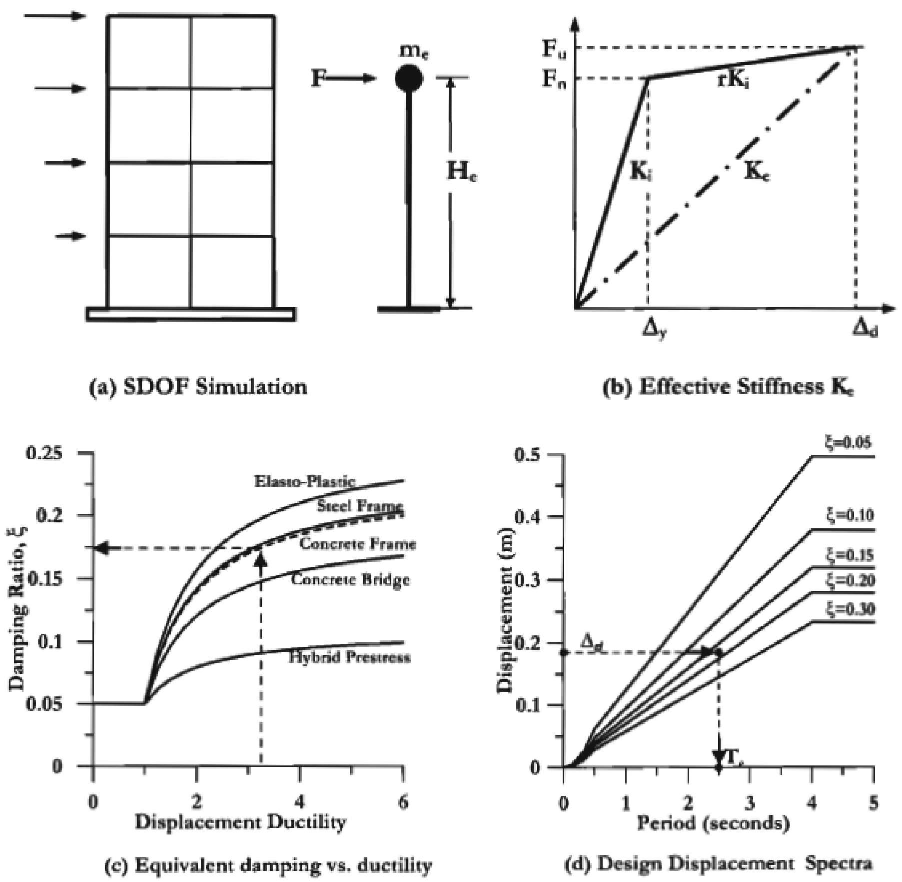

Figure 3.3: Fundamentals of DBD

Δ_d = Design displacement of the system

This base shear is distributed along the height of the building in a triangular profile using the Equation (3.5).

The design concept is thus very simple. Careful consideration is however also necessary for the distribution of the design base shear V_B to the different discretized mass locations, and for the analysis of the structure under the distributed seismic force.

3.3.2 Important Parameters

I) **Yield and Design Displacement**

The moment curvature distribution of a column is shown in Figure 3.4. The dashed line gives the bilinear idealization of the moment curvature distribution. The plastic hinge length at the base is L_P over which strain and curvature are considered to be equal to the maximum value at the column base. The plastic hinge length incorporates the strain penetration length L_{SP} as shown in Figure. Further, the curvature distribution higher up the column is assumed to be linear, in accordance with the bilinear approximation to the moment-curvature response.

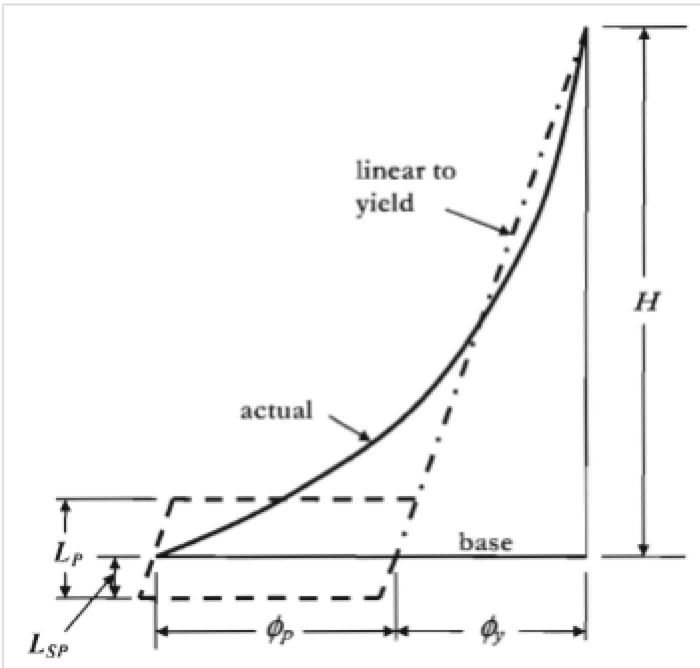

Figure 3.4: Idealization of Moment Curvature Distribution

The strain penetration length, L_{sp} may be taken as,

$$L_{sp} = 0.022 \times f_y \times d_{bl} \ (f_y \ in \ MPa) \tag{3.8}$$

where f_y and d_{bl} are the yield strength and diameter of the longitudinal reinforcement.

The plastic hinge length, L_p, (for beams and columns) is given as,

$$L_p = k \times L_c + L_{sp} \tag{3.9}$$

where k= 0.2 x (f_u/f_y -1) $\leq$ 0.08

where, L_c = length from the critical section to the point of contraflexure in the member and f_u = ultimate steel stress. The yield displacement is required for two reasons:

i) To calculate design displacement (Δ_u)

ii) To calculate displacement ductility ($\mu = \Delta_u/\Delta_D$)

The yield displacement for a vertical SDOF cantilever can be satisfactorily approximated for design purposes as:

$$\Delta_y = \phi_y(H + L_{sp})^2/3 \tag{3.10}$$

The design displacement can now be estimated as:

$$\Delta_{d,ls} = \Delta_y + \Delta_p = \Delta_y(H + L_{sp})^2/3 + (\phi_{ls} - \phi_y) \times L_p \times H \tag{3.11}$$

where ϕ_{ls} is the limit state curvature and is the minimum of the following two:

$\phi_{ls,c} = \varepsilon_{c,ls}$ / c (concrete compression)

$\phi_{ls,c} = \varepsilon_{s,ls}$ /(d-c) (reinforcement tension)

where c is the depth of neutral axis, $\varepsilon_{c,ls}$ and $\varepsilon_{s,ls}$ are the limit-state strains for concrete compression and steel tension respectively.

It has been shown by Priestley [4] that, yield curvature for RC and masonry structures is independent of reinforcement content and axial load level, but is a function of yield strain and section depth. Governing equation of yield curvature is given as, ϕ_y = C x ε_y/h

where C = constant, ϕ_y = yield strain of the longitudinal reinforcement and h = section depth.

Based on work done by Priestley, The following are the equations for yield curvature of some different section shapes provide adequate approximations:

Circular Concrete Column: $\phi_y = 2.25\ \varepsilon_y\ /D$

Rectangular Concrete Column: $\phi_y = 2.10\ \varepsilon_y\ /\ h_c$

Rectangular Concrete Wall: $\phi_y = 2.00\ \varepsilon_y\ /\ \text{lw}$

Symmetrical Steel Section: $\phi_y = 2.10\ \varepsilon_y\ /\ h_s$

Flanged Concrete Beam: $\phi_y = 1.70\ \varepsilon_y\ /\ h_b$

where ε_y , is the yield strain of the flexural reinforcement (= fy/Es) and D, h_c, lw, h_s and h_b are the section depths of the circular column, rectangular column, rectangular wall, steel section and anged concrete beam sections, respectively. The above equations give the curvature at the yield of the equivalent bilinear approximation to the moment-curvature curve.

For reinforced concrete and structural steel frames, the yield drift can be developed from the yield curvature as given below:

θ_y = 0.5 x ε_y x L_b/ h_b for Reinforced Concrete Frame

θ_y = 0.65 x ε_y x L_b/ h_b for Structural Concrete Frame

where L_b is the beam span, and h_b is the concrete or steel beam depth.

II) **Equivalent Viscous Damping**

The design procedure requires relationship between displacement ductility and equivalent viscous damping, as shown in Figure 3.3(c). The equivalent viscous damping is consists of elastic and hysteretic damping, i.e.,

$\xi_{sys} = \xi_{el} + \xi_{hyst}$

Here the hysteretic damping ξ_{hyst} is governed by the hysteresis rule applied for the structure being designed. Typically, the elastic damping ratio is adopted for concrete structures as 0.05, related to critical damping.

Dwairi and Kowalsky [19] represented the hysteretic damping component of response as,

ξ_{hyst} = C x (μ - 1)/(μ x π)

where the coefficient C is depended on the hysteresis rule. Priestley [4] has presented following equations for equivalent viscous damping as,

Concrete wall building; Bridges: $\xi_{eq} = 0.05 + 0.444(\mu -1)/(\mu\ \pi)$

Concrete frame building: $\xi_{eq} = 0.05 + 0.565(\mu -1)/(\mu\ \pi)$

It is important to note here that above equations are applicable for the elastic damping co-efficient 0.05, as value of co-efficient 'C' is not valid for other levels of elastic damping.

III) Design Displacement Spectra

For using this method, spectral displacement spectra is generated from the given spectral acceleration from the code as shown in the figure below.

This is done using the Equation (3.12):

$$A = \omega^2 \times D = [4\pi^2/T^2] \times D \tag{3.12}$$

where A and D = Spectral Acceleration and Spectral Displacement respectively.

We know that the base shear is given by:

V_B = Z/2 x I/R x Sa / g x We

= Z/2 x I/R x Sa x me

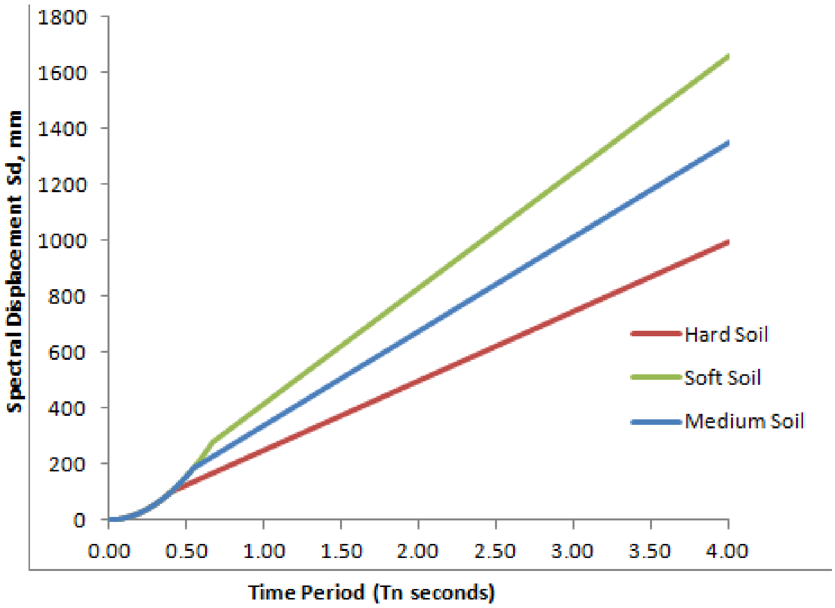

Figure 3.5: IS Code Design Displacement Spectra

$V_B = 4\pi/T^2$ x m x D x Z/2 x m.f. x I

$V_B = 4\pi/T_e^2$ x m x D

Hence, the design displacement value will be entered in the code based displacement spectrum given in Figure 3.5, and the time period T will be obtained. This time period T needs to be modified to include the effects of zone, damping and importance factor as follows:

$$Te^2 = \frac{T2}{(Z/2) \times m.f. \times I} = 2 \times T^2/[Z \times m.f. \times I] \tag{3.13}$$

3.4 Comparison of FBD and DBD

The comparison of FBD and DBD is being discussed as given in the following Table 3.4 below:

Table 3.1: Comparison among FBD and DBD

Sr. No.	**Force Based Design**	**Displacement Based Design**
1	Stiffness is assumed based on the plan dimensions. The time period is calculated from the empirical equations from the code.	The time period is the one of the products of the design. Strength and stiffness are not variables in the procedure, but they are the end results.
2	Seismic codes specify values for the factor, R, depending upon the material of construction and the type of structural system used. However, these values appear to be arbitrary, are difficult to justify, and do not appear to have been established consistently by experiment or analysis.	No such force reduction factors are being used. Instead the actual ductility demand is calculated. Then hysteresis damping of the system is calculated, which is then used to find the time period of the structure.
3	A displacement check is usually made after the structural members satisfy the force requirement. Displacements are treated in a somewhat cursory manner in FBD and are checked at the end of the design process only. There appears to be a lack of concern about the implied inelastic displacements when values of R greater than 1.0 are used.	Displacement is the basic input quantity of this method. In DBD procedure, seismic design is performed by specifying a target displacement rather than a displacement limit.
4	This method is based on the initial stiffness calculated from the section sizes.	This method is based on the secant stiffness.
5	In this method, it is assumed, by equal displacement approximation, that by using the response reduction factor, the relative level of ductile response is assured.	It directly addresses the inelastic nature of a structure during an earthquake.

3.5 Illustrative Problem

Figure 3.6 shows the plan of a single storey building modelled as Single Storey of Building (SDOF) system. The geometric and material properties used is defined in the following section. Seismic demand of the building is calculated from both, FBD and DBD.

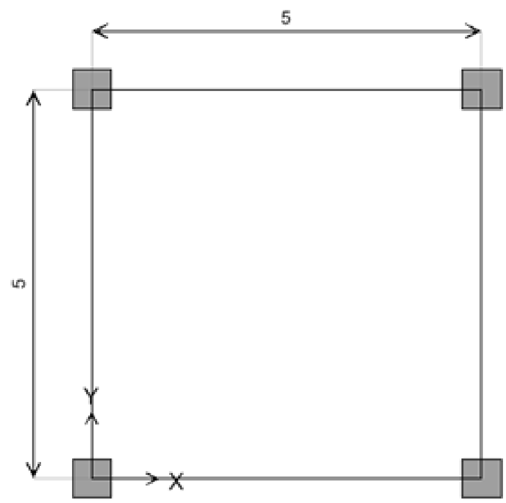

Figure 3.6: Plan of a Single Storey Building

3.5.1 Building Configuration

Following parameters defines the building configuration:

Slab = 150mm thick, grade M20

Columns = 500mm x 500mm, grade M25

Live load intensity considered = 3kN/m^2

Floor Finish = 1kN/m^2

Earthquake Zone = V

Zone Factor, Z = 0.36

Importance Factor, I=1

Soil type = Medium

Storey height = 4m

Parapet = 150 mm thick on periphery, 1m high

Density of concrete = 25kN/m3

Density of masonry = 25kN/m3

Grade of longitudinal steel, fy = 415 MPa

Grade of transverse steel, fy = 415 MPa

3.5.2 Load Calculation

The gravity as well as seismic weight calculations are as follows:

Slab = 5 x 5 x 0.15 x 25 = 93.75kN

Beams = 4 no.s x 0.23 x 0.45 x 5 x 25 = 51.75 kN

Columns = 4 no.s x 0.5 x 0.5 x 4 x 25= 100kN

Parapet = 4 x 1 x 0.15 x 5 x 20 = 60 kN

Hence, Total Dead Load = 330.5 kN

Live Load (LL) = 5 x 5 x 3 =75kN

Floor Finish (FF) = 25 kN

Seismic Weight, We = (330.5-100/2) +0.25x75 = 299.25kN

(LL=3 kN/m^2, hence as per IS 1893:2002, 25% of LL is considered, also half column weight in considered for the lumped mass at roof level)

3.5.3 Force Based Design

The FBD carried out as per IS 1893 (Part 1): 2001 is given below:

Stiffness, K_e= 4 x 12EI/L^3

= 4 x 12 x [25000 x 10^3] x [1 / 12 x 0.5^3 x 0.5] / 4^3

= 9765625 N/m

Mass, m_e = 299.25 x 103 / 9.81 = 30504.6 kg

Natural frequency, ω= $\sqrt{ke/me}$ = 56.58 rad/s

Time period, T = 0.11 sec

A_h = Z/2 x I/R x Sa/g = 0.36/2 x 1/3 x 2.50 = 0.15

Therefore, Base shear, V_B = 0.15 x 299.25 = 45kN

3.5.4 Displacement Based Design

Following section discusses the Displacement Based Design of the SDOF system.

Total DL+LL = 330.5 + 75 = 405.5kN

Factored Load = 1.5 x 405.5 = 608kN

Factored Axial load on each column = 608/4 = 152kN

Provide 12 no.s - 16mm dia. bars in all four columns.

Also, provide 2 legged - 8mm dia. stirrups @ 150mm c/c spacing.

From RC Analysis [8], yield curvature and ultimate curvature comes out to be, ϕ_y = 0.0115 per m ϕ_u = 0.1506 per m respectively.

The yield displacement is given by Equation (3.14):

$$\Delta_y = \phi_y(H + L_{sp})^2/3 \tag{3.14}$$

where L_{SP} = 0.022 x fy x d_{bl} = 146.08mm

k= 0.2 x (fu/fy -1) $\leq$ 0.08

Therefore, k = 0.034

L_p = k x L_c + L_{sp} = 0.034 x 4000 +146.08 = 282mm

where L_c = Length from the critical section to the Point of contraflexure = 4000mm

Yield Displacement, Δ_y = 0.0115 x $(4000 + 282)^2$ /3 = 70.23mm

Ultimate Displacement, Δ_u = Δ_y + (ϕ_u - ϕ_y) x L_p x H_1

where H_1 = Distance from the centre of the plastic hinge to the point of contraflexure for members in single bending = 4000mm

Therefore, Δ_u = 70.23 + (0.1506 - 0.0115) x 282 x 4000 = 157mm

Displacement ductility, = Δ_u /Δ_y = 157/70.23 = 2.23

Table 3.2: Comparison of FBD and DBD - SDOF system

Response Quantities	**Force Based Design**	**Displacement based design**
Time Period T, sec	0.11	1.414
Stiffness, Ke (N/m)	9765625	602318
Base Shear, V_B (kN)	45	94.56
Ductility	3	2.23

Equivalent hysteresis damping, ξ_{eq} = 0.05 + 0.565(μ -1)/(μ π) = 0.149 = 14.9 %

Modification Factor for damping, m.f. = 0.702 from IS 1893 : 2002

From IS 1893 displacement Spectra, for displacement = 157mm, time period reads out to be T = 0.5027.

As derived earlier,

Te^2 = 2 x T^2 / [Z x m.f. x I] = 2 x 0.50272 /[0.36 x 0.702 x 1] = 2.0 sec^2

Hence, T_e = 1.414 sec

Effective stiffness, K_e = 4 π^2/T^2 x m = 602318 N/m

Base Shear, V_B = K_e x Δ_u = 602.318 x 0.157 = 94.56 kN

3.6 Results and Discussions

The values of various response quantities like Time period, Stiffness, Base Shear and Ductility are tabulated in the below given table 3.2 for FBD and DBD. It shows the comparison of various quantities between FBD and DBD.

As can be seen from the above table, the time period of FBD is coming out to very less when compared to DBD, also the base shear is also lesser in FBD than DBD. The stiffness of the system comes out to be less in DBD than FBD. Also, the calculated ductility as per DBD comes out to be much lower as compared to the assumed ductility for RC frame as 3 as per IS 1893:2002. Hence, the FBD as given in code is proved to be unsatisfactory, if actual inelastic behavior is to be considered.

3.7 Summary

In this chapter, various aspects of DBD like yield and design displacement, equivalent viscous damping, design displacement spectra and the consideration of zone effect are discussed. In the present study, RC-Analysis software is used in order to determine moment-curvature relationship for a column section. Illustrative example consists of a single storey building which is solved by FBD and DBD and parameters like time period, stiffness, base shear and ductility are compared.

Chapter 4

Shear Wall Building

4.1 Introduction

In this chapter, an attempt is made to study the displacement based design of Shear Wall Building and to compare it with force based design. For this, two buildings having the same plan dimension 25m x 18m but different number of storeys viz. 15 and 25 are chosen.

4.2 Consideration of Zone Factor and Damping

The influence of zone factor and damping on DBD is explained in this section. The force based codal base shear equation is given by:

V_B = Z/2 x I/R x Sa / g x We

= Z/2 x I/R x Sa x me

= Z/2 x I/R x ω^2 x D x me

where $\omega = 2\ \pi$ /T

The factor R is insignificant in the Displacement based Design, hence ignored in the base shear equation.

$$V_B = 4\pi/T^2 \times m_e \times D \times Z/2 \times m.f. \times I \tag{4.1}$$

For medium soil sites,

$$Sa/g = \begin{cases} 1 + 15T & 0.00 \leq \text{T} \leq 0.10 \\ 2.50 & 0.10 \leq \text{T} \leq 0.55 \\ 1.36/T & 0.55 \leq \text{T} \leq 4.00 \end{cases}$$

$$Hence, S_d = D = S_a \times T^2/4\pi^2 = 1.36 \times g \times T/4\pi^2 = 0.338T \tag{4.2}$$

Hence, D=0.338T or T=D/0.338

$$Hence, V_B = 4\pi^2 \times m \times D/(D/0.338)^2 \times Z/2 \times m.f. \times I = 2.255 \times Z \times me \times m.f. \times I/D \tag{4.3}$$

The above derived equation is only valid for (i) Medium soil sites and (ii) 0.55 $\leq$ T $\leq$ 4.00.

Similarly for other cases too, similar equations can be derived. This study includes the building which is located in Medium soil sites and it is a high rise building having time period greater than 0.55 seconds.

4.3 Substitute Structure Method

The MDOF wall-frame system is converted into a SDOF system by using the substitute structure method. The relation of the variables between the MDOF structure and the SDOF structure are derived through the equal work principle. In general, this principle states that the work done by the MDOF force is equivalent to the work done by the SDOF force system, or (FΔ)MDOF = (FΔ)SDOF.

4.3.1 Design SDOF displacement

The design displacement of the substitute structure is given by:

$$\Delta_D = \frac{\sum_{i=1}^{n} m_i \times \Delta_i^2}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{4.4}$$

4.3.2 Effective Height

The Effective height of the substitute structure is given by:

$$He = \frac{\sum_{i=1}^{n} m_i \times \Delta_i \times Hi}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{4.5}$$

4.3.3 Effective Mass

The Effective Mass of the SDOF system is given by

$$me = \frac{\sum_{i=1}^{n} m_i \times \Delta_i}{\Delta_d} \tag{4.6}$$

4.4 Problem Formulation

The building shown in Figure 4.1 is 15 storeys high. Following parameters defines the building configuration:

Building Data:

No. Of storeys: 15

Storey height: 3m

Building height: 45m

Plan Dimensions: 25m x 18m

Concrete Grade: M25

Steel Grade: Fe415

No. Of bays in X-Direction: 5

No. Of bays in Y-Direction: 3

Size of Beams: 300mm x 600mm

Earthquake Zone: Zone-V (Z=0.36)

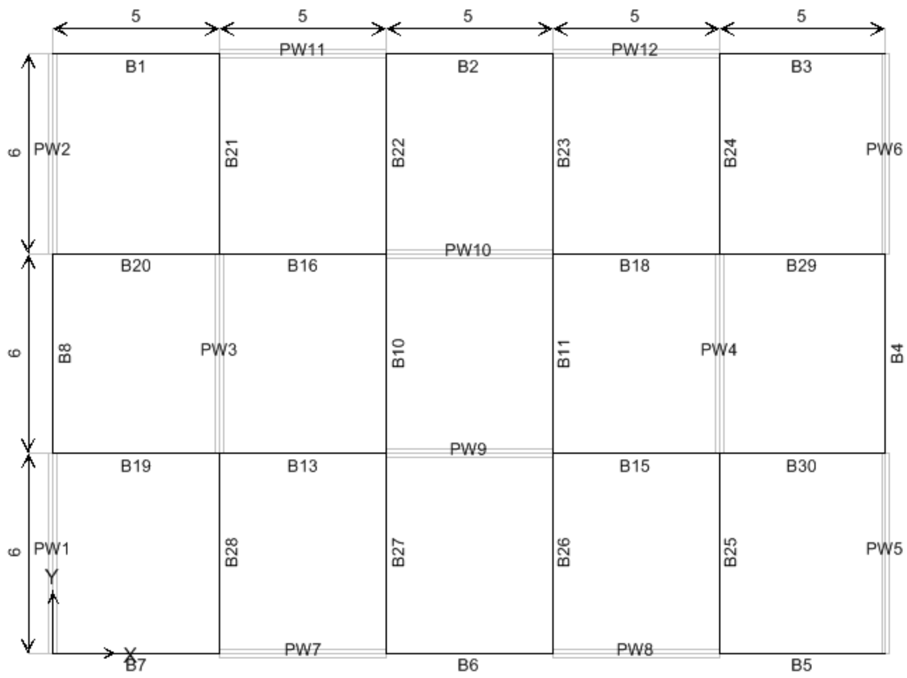

Figure 4.1: Plan of the Shear-Wall Building

Soil type: Medium

Thickness of Shear Walls: 250mm

Live Load = 3 kN/m^2 on all floors (including roof)

Live Load to considered for Seismic Analysis = 25% on Floors

= 0% on Roof

Importance Factor = 1

4.4.1 Load Calculation

The gravity as well as seismic weight calculations are as follows:

Shear Walls = 45 x 6 x [5 x 0.25 + 6 x 0.25] x 25 = 18563 kN

Floor Finish = 1 x 18 x 25 x 15 = 6750 kN

Beams Weight = 15 x [5 x 14 + 6 x 12] x 0.30x 0.60x 25 = 9585 kN

Slab Weight = 0.15 x 25 x 15 x 18 x 25 = 25313 kN

Total Dead Load (DL) = 60211 kN

Total Live Load for Floors, except Roof = 3 x 18 x 25 x 14 = 18900 kN

Total Live Load for Roof = 3 x 18 x 25 = 1350 kN

Total Seismic Weight of the Building,

We = 60211 + 0.25 x 18900 + 0 x 1350 -18563/(2x15) = 64314 kN

Seismic Wt of typical storey,

Wi = 60211/15 + 1350 x 0.25 = 4352 kN = 443629 kg

Seismic Wt of roof,

Wr = (60211 - 18563/2)/15 + 0 x 1350 = 3395 kN = 346106 kg

4.4.2 Force Based Design

The conventional FBD analysis has not included here as it is a standard procedure followed from IS 1893. For detailed calculations on FBD, refer Appendix A.

4.4.3 Displacement Based Design

The Displacement based design for the longitudinal direction i.e. X - Direction is explained step by step in this section. The Displacement based design for Y- direction is carried out the same manner as it is done for the X-direction. Results are shown in the further sections.

STEP I. **Material Constants**

First of all, important parameters required for the design are calculated:

The reinforcement grade is Fe 415. Hence, fy= 415 MPa.

The expected yield strength of the reinforcing bar is

fye=1.1fy = 1.1 x 415 = 456.5 MPa

The yield strain of the reinforcement is given by:

ε_y = fye/E

where E = Modulus of Elasticity of Steel = 2x 10^5 MPa

Hence, ε_y = 456.6/(2x10^5) = 0.0022825

The yield curvature for rectangular wall sections is given by:

ϕ_{yw}= 2 x ε_y / lw = 2 x 0.0022825 / 5 = 0.000913 per m

STEP II. **Design Displacement Profile**

The yield displacement profile of the shear wall building is given by:

$$\Delta_{yi} = \varepsilon_y/l_w \times H_i^2 \times (1 - (1/3) \times (H_i/H_n)) \tag{4.7}$$

The design displacement profile is given by:

$$\Delta_i = \Delta_{yi} + \Delta_{pi} = \varepsilon_y/l_w \times H_i^2 \times [1 - [H_i/3H_n]] + (\phi_m - 2\varepsilon_y/l_w)L_p H_i \tag{4.8}$$

Roof yield displacement, Δ_{Yi} = 2/3 x θ_y x (H_n + L_{sp})

Roof level ultimate or total displacement, Δ_{Di} = Δ_{Yi} + θ_p x H_n

In this, first material strains is considered, then checked if codal drift governs:

Wall Material Strain Case:

With no information on the strain at the maximum stress level for the wall reinforcing steel, a conservative value of $\varepsilon_{su} = 0.10$ is used.

Hence, the damage control curvature is given by:

$\phi_{dc} = 0.072/l_w$

Plastic Hinge length is given by:

$$L_P = kH_e + 0.1l_w + L_{SP} \tag{4.9}$$

Assume effective height H_e as a fraction of H_n as an initial assumption.

And,

l_w = length of the walls in the considered direction

k =0.2(fu/fy - 1) $\leq$ 0.08

L_{sp} = 0.022 x f_{ye} x d_{bl}, where d_{bl} = dia. of bars as longitudinal reinforcement in the wall.

With no information on the strain at the maximum stress level for the wall reinforcing steel, a conservative value of ε_{su} = 0.10 is used.

Hence, the damage control curvature is given by:

ϕ_{dc} = 0.072/l_w =0.072/5 = 0.0144 per m

Plastic Hinge length is given by:

$$L_P = kH_e + 0.1l_w + L_{SP} \tag{4.10}$$

Assume effective height $H_e = 0.75 \times H_n$

So, H_e= 0.75 $\times$ 45 = 33.75 m

And,

l_w = length of the walls in X-direction = 5 m

k =0.2(f_u/f_y - 1) $\leq$ 0.08

From IS 1786 : 1985, f_u = 485 MPa (minimum)

Therefore, k = 0.2 x (485/415 - 1) = 0.0337

L_{sp} = 0.022 x f_{ye} x d_{bl} =0.022 x 456.5 x 20 = 200.86 mm, assuming 20 mm dia. bars as longitudinal reinforcement in the wall.

Hence, substituting the values, Plastic Hinge length comes out to be, L_p = 1.84 m

Check if the code based drift limit at H_n is exceeded:

Yield drift : $\theta_y = \phi_{yw}$ x $(H_n + L_{sp})$ /2

plastic drift : $\theta_p = (\phi_{dc}$ - $\phi_{yw})$ x L_p

Total drift: $\theta_{cf} = \theta_y + \theta_p$

Then it is checked if it exceeds the code based drift limit and the lower of the two, governs the wall design.]

Yield drift : θ_y= 0.000913 x (45+0.201)/2 = 0.0206 rad

plastic drift : θ_p= (0.0114 - 0.000913) x 1.84 = 0.0248 rad

Total drift: θ_{cf}= 0.0206 + 0.0248 = 0.0454 rad

This exceeds the code based drift limit of 0.004 x 4 [Ductility factor for Ductile Shear Wall buildings as per IS 1893(Part 1) :2002) = 0.016, hence code drift limit governs the wall design.]

Hence, Governing θ_{cf} = 0.016 rad

The yield drift is greater than the total drift. Hence, limiting the yield drift to the total permissible drift,

Governing θ_y = 0.016 rad

Governing θ_p = 0.016 - 0.016 = 0.00 rad.

It is to be noted here that the structure is capable of providing inelastic or plastic behavior, but because the permissible drift limit is low, upto that limit the structure will behave elastically.

Higher Mode Effects:

Due to higher mode effects on tall buildings, the shear and moments on the higher storeys gets amplified. This needs to be incorporated somehow in DBD as DBD is essentially based on the first inelastic mode response of the structure. Hence, the drift limits needs to be reduced to compensate for the higher mode effects by the factor ω_θ.

The drift limits needs to be reduced to compensate for the higher mode effects.

$$\omega_\theta = 1 - (n - 5)/100 \times (0.25) \tag{4.11}$$

This correction factor will have negligible influence for n $\leq$ 10.

where n = no. of storeys,

ω_θ = 1 - (15 - 5)/100 x 0.25 = 0.975

Hence, the reduced design drift is,

θ_c = 0.975 x 0.016 = 0.0156 rad

The reduced yield drift is,

θ_y = 0.975 x 0.016 = 0.0156 rad

Roof yield displacement, Δ_{Yi} = 2/3 x θ_y x (H_n + L_{sp})

= 2/3 x 0.0156 x (45 + 0.201) = 0.470 m

Roof level ultimate or total displacement, $\Delta_{Di} = \Delta_{Yi} + \theta_p$ x H_n

= 0.470 + 0.0 x 45 = 0.470 m

STEP III. **Displacement Profile Calculations**

Calculations necessary to determine the displacement profile and hence, the effective height and the design displacement for wall is summarized in below given table 4.1.

STEP IV. **Effective Height**

From Table 4.1, the effective height is given by:

Table 4.1: Displacement Profile Calculation

Floor i	Hi (m)	mi (kg)	θ_{yi} (rad)	Δ_{yi} (m)	θ_{pi} (rad)	Δ_{pi} (m)	Δ_{di} (m)	mi x Δ_{di}	mi x Δ_{di}^2	mi x Δ_{di} x Hi
15	45	346106	0.0156	0.468	0.0000	0.000	0.468	161978	75806	7288992
14	42	443629	0.0156	0.421	0.0000	0.000	0.421	186887	78730	7849265
13	39	443629	0.0156	0.375	0.0000	0.000	0.375	166341	62370	6487289
12	36	443629	0.0156	0.329	0.0000	0.000	0.329	146163	48157	5261879
11	33	443629	0.0156	0.285	0.0000	0.000	0.285	126540	36094	4175805
10	30	443629	0.0156	0.243	0.0000	0.000	0.243	107654	26124	3229619
9	27	443629	0.0156	0.202	0.0000	0.000	0.202	89691	18133	2421660
8	24	443629	0.0156	0.164	0.0000	0.000	0.164	72836	11958	1748054
7	21	443629	0.0156	0.129	0.0000	0.000	0.129	57272	7394	1202710
6	18	443629	0.0156	0.097	0.0000	0.000	0.097	43185	4204	777323
5	15	443629	0.0156	0.069	0.0000	0.000	0.069	30758	2133	461374
4	12	443629	0.0156	0.045	0.0000	0.000	0.045	20177	918	242129
3	9	443629	0.0156	0.026	0.0000	0.000	0.026	11627	305	104640
2	6	443629	0.0156	0.012	0.0000	0.000	0.012	5290	63	31743
1	3	443629	0.0156	0.003	0.0000	0.000	0.003	1353	4	4060
0	0	0		0	0	0	0	0	0	0
Sum		6556911		2.870		0.000	2.870	1227752	372392	41286543

$$He = \frac{\sum_{i=1}^{n} m_i \times \Delta_i \times Hi}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{4.12}$$

Therefore, He = 41286543 / 1227752 = 33.63 m

STEP V. **Design SDOF Displacement**

From table 4.1, the design displacement of the SDOF substitute structure is given by:

$$\Delta_D = \frac{\sum_{i=1}^{n} m_i \times \Delta_i^2}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{4.13}$$

Δ_D = 372392/122752 = 0.303 m

STEP VI. **Yield SDOF Displacement**

The yield displacement the SDOF substitute structure is calculated substituting He in above equation,

$\Delta_y = \varepsilon_y$ / l_w x H_e^2 x (1 - H_e / H_n)

= 0.0022825 / 5 x 33.63^2 x (1 - 33.63/45)

= 0.303 m

STEP VII. **Equivalent Damping**

The equivalent viscous damping depends on the ductility demand.

The ductility demand for wall is respectively given by

$$\mu = \Delta_D/\Delta_Y \tag{4.14}$$

where Δ_D = Design Displacement of SDOF system, Δ_Y = Yield Displacement of SDOF system.

The effective damping is given by:

ξ_{sys} = 0.05 + 0.444 (μ -1)/ (μ x π)

The ductility of walls is:

$$\mu_W = \Delta_D/\Delta_{YW} \tag{4.15}$$

μ_W = 0.303 / 0.303 = 1.00

The effective damping is given by:

ξ_W = 0.05 + 0.444 (μ_W -1)/ (μ_W x π) = 0.0500 = 5.0 %

Hence, the modification factor(m.f.) for damping as per table 3 of IS 1893 (Part 1):2002,

m.f. = 1

STEP VIII. **Effective Mass**

The Effective Mass of the SDOF system is given by

$$m_e = \frac{\sum_{i=1}^{n} m_i \times \Delta_i}{\Delta_d} \tag{4.16}$$

Hence, me = 1227752/ 0.303

= 4047822 kg

STEP IX. **Base Shear**

The Base Shear of the SDOF system as per the formula derived in section 4.2, is given by

V_B = 2.255 x Z x m_e x m.f. x I / Δ_d

= 2.255 x 0.36 x 4047822 x 1 x 1 x 0.303

= 10834 kN

STEP X. **Effective Stiffness**

The Effective Stiffness of the SDOF system is given by

Ke = V_B / Δ_D = 10834 / 0.303 = 35718 kN/m

STEP XI. **Effective Time Period**

The Effective Time Period of the SDOF system is given by

Te = 2π x $\sqrt{me/ke}$

= 2 x 3.14 x $\sqrt{4047822/35718000}$

= 2.12 seconds

4.5 Parametric Study

Parametric study is carried out by performing the DBD for 15 and 25 storey buildings for both the directions. The below shown

4.2 shows the elevations of 15 and 25 storey buildings respectively.

Also, for both the buildings, two cases are taken, one in which the codal drift limit is considered and other in which the codal drift limit is ignored. The former is a traditional approach, while the latter is done to know the ductility capacity of the building and its effect on base shear and other quantities.

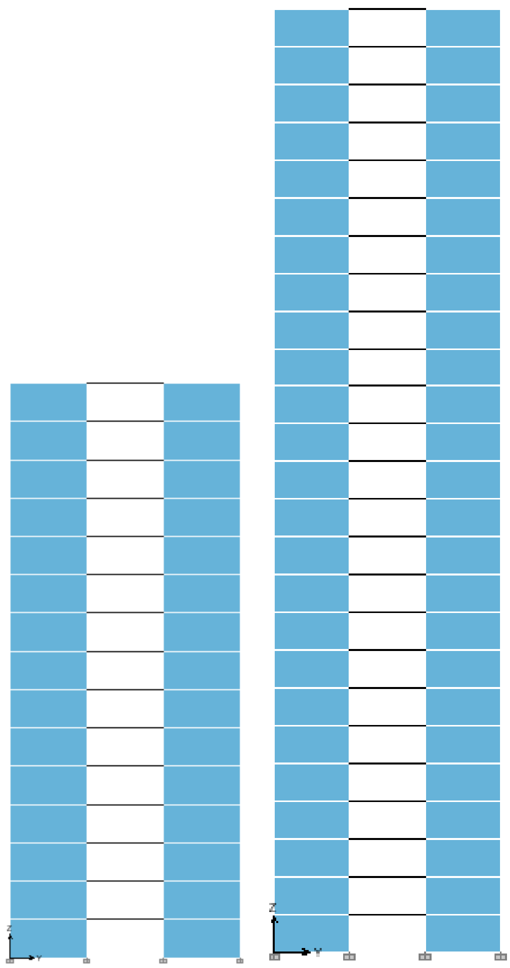

Figure 4.2: Elevation of 15 and 25 Storey Buildings

4.6 Results and Discussions

In this section, the plots are shown showing the variation of various quantities between FBD and DBD across the height of the structure. Also, the nature plots are found to be almost similar for 15 and 25 storey shear wall building.

4.6.1 15 Storey Building

The plots showing the comparison of FBD and DBD for 15 storey building for the X and Y directions are shown in this section.

X - DIRECTION

The plots for the X - Direction are as follows:

Figure 4.3 shows the comparison of the displacement profile of the building by FBD and DBD. Figure 4.4 shows the comparison of drift of the building by FBD and DBD. The yield and design displacement is the same for DBD as there is no ductility demand because of the codal drift restriction. The displacements and drifts is much higher in case of DBD than FBD - elastic or inelastic.

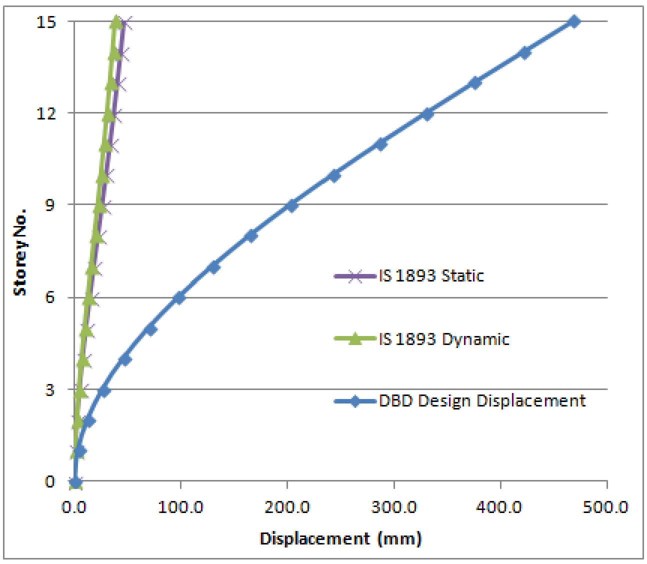

Figure 4.3: Displacement Comparison by FBD and DBD- X -Direction

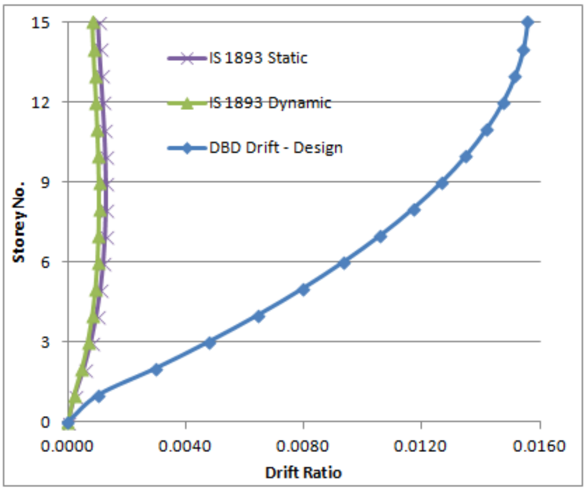

Figure 4.4: Drift Variation by FBD and DBD - X -Direction

Figure 4.5 and Figure 4.6 shows the variation of the lateral forces and storey shear, respectively across the height of the building, by FBD and DBD. Lateral storey forces and hence, the storey shear values for DBD are much higher than FBD.

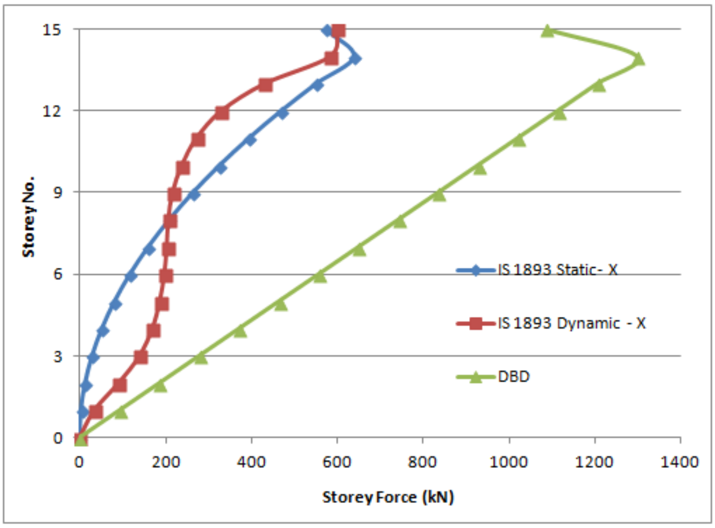

Figure 4.5: Lateral Forces Comparison by FBD and DBD - X -Direction

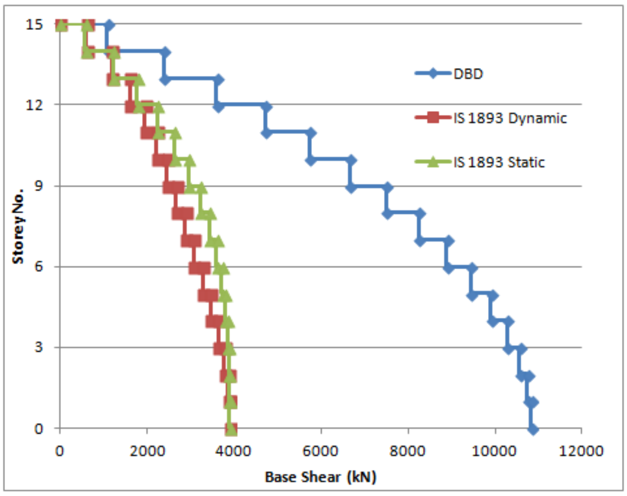

Figure 4.6: Variation of the Storey Shear across the height- X -Direction

Figure 4.7 shows the Overturning moment distribution across the height of the building.

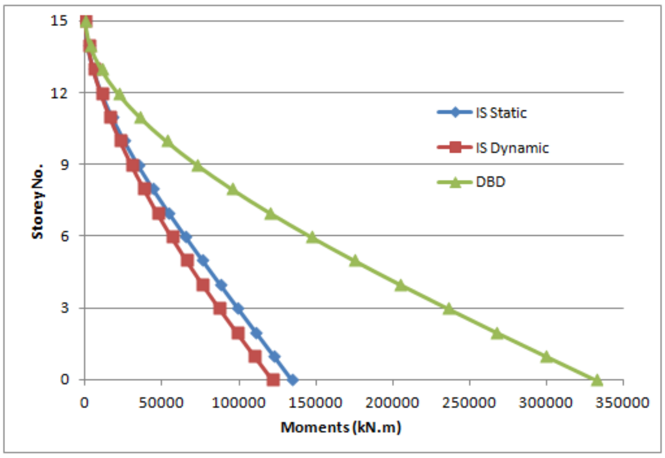

Figure 4.7: Overturning Moment Comparison - X -Direction

Y - DIRECTION

The plots for the Y - Direction are as follows:

Figure 4.8 shows the comparison of the displacement profile of the building by FBD and DBD. Figure 4.9 shows the comparison of drift of the building by FBD and DBD.

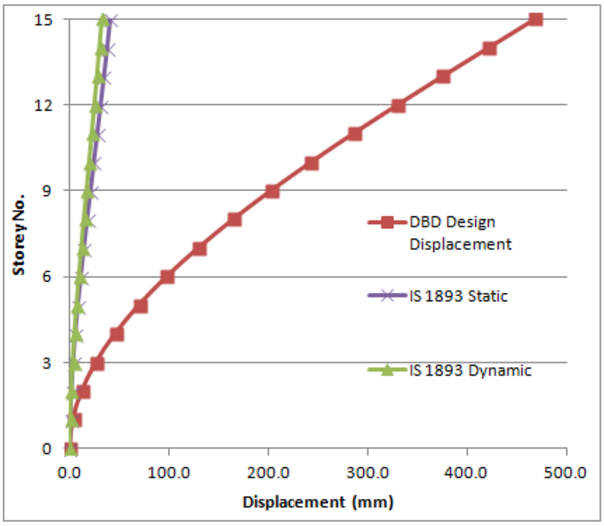

Figure 4.8: Displacement Comparison by FBD and DBD- Y -Direction

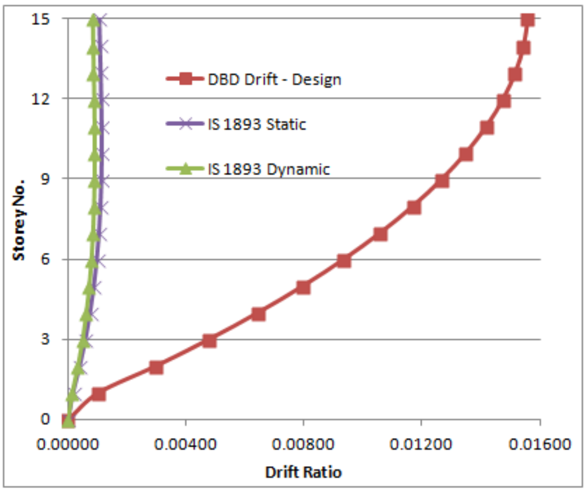

Figure 4.9: Drift Variation by FBD and DBD - Y -Direction

Figure 4.10 and Figure 4.11 shows the variation of the lateral forces and storey shear, respectively across the height of the building, by FBD and DBD. As expected, the values for DBD are much higher as compared to FBD.

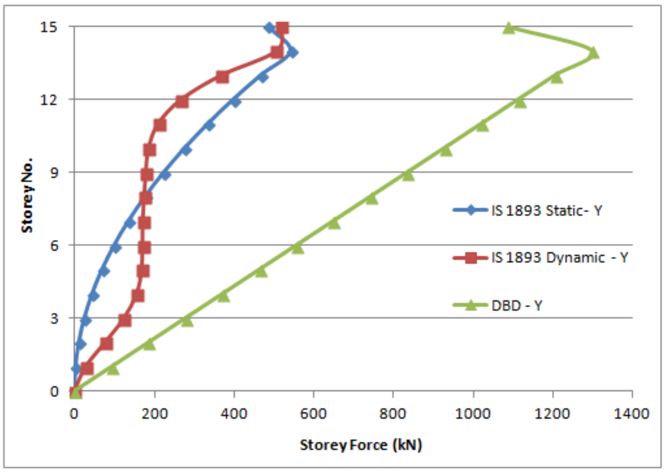

Figure 4.10: Lateral Forces Comparison by FBD and DBD - Y -Direction

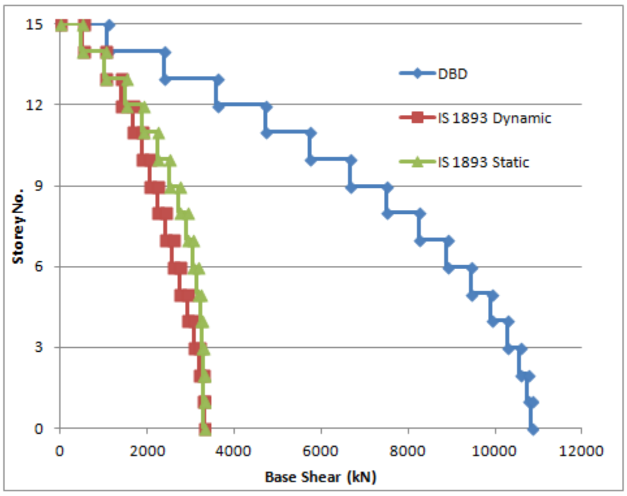

Figure 4.11: Variation of the Storey Shear across the height- Y -Direction

Figure 4.12 shows the Overturning moment distribution across the height of the building. The overturning moment at the base is found to be quite higher as compared to DBD.

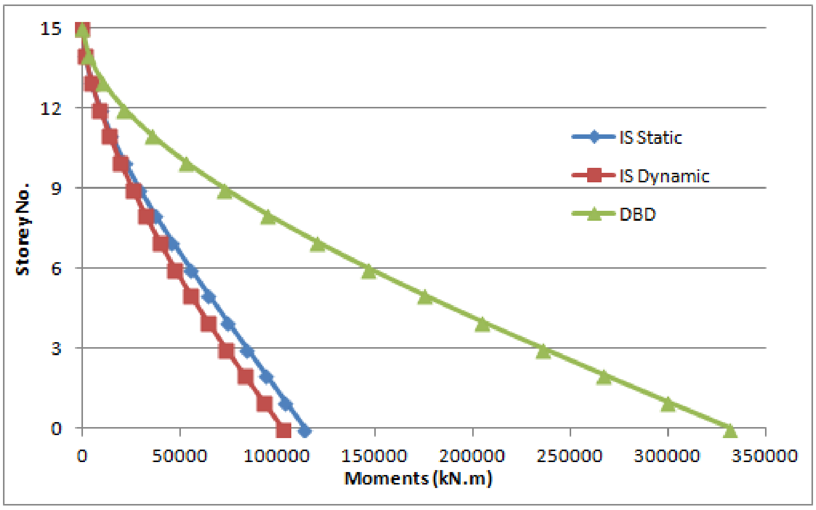

Figure 4.12: Overturning Moment Comparison - Y -Direction

4.6.2 25 Storey Building

The plots showing the comparison of FBD and DBD for 25 storey building for the X and Y directions are shown in this section.

X - DIRECTION

The plots for the X - Direction are as follows:

Figure 4.13 shows the comparison of the displacement profile of the building by FBD and DBD.

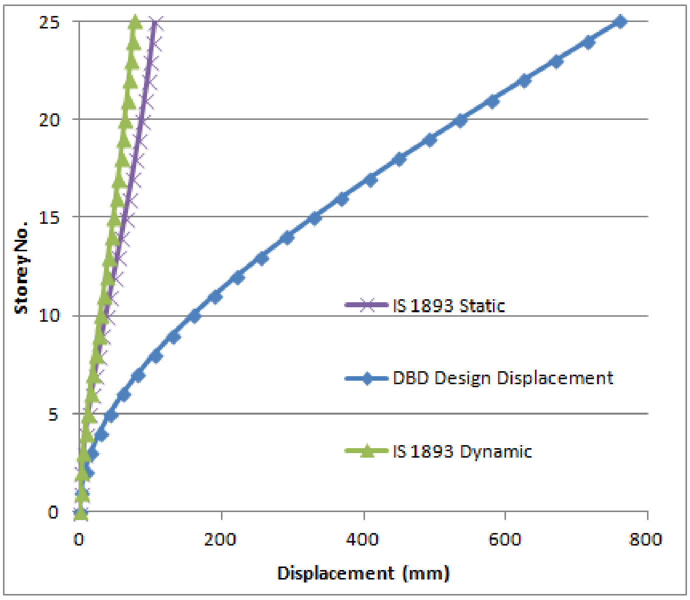

Figure 4.13: Displacement Comparison by FBD and DBD- X -Direction

Figure 4.14 shows the comparison of drift of the building by FBD and DBD.

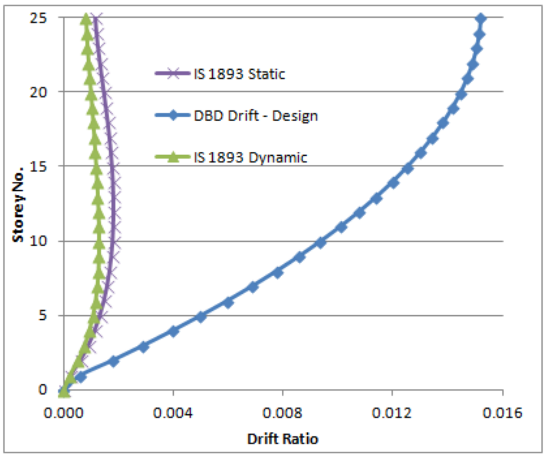

Figure 4.14: Drift Variation by FBD and DBD - X -Direction

Figure 4.15 shows the variation of the lateral forces across the height of the building, by FBD and DBD.

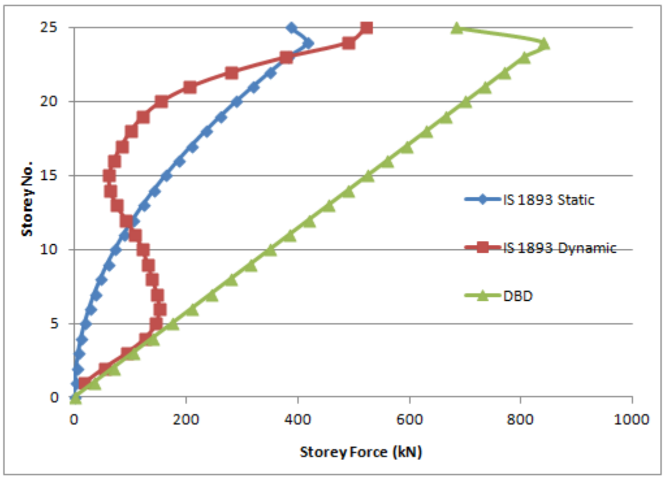

Figure 4.15: Lateral Forces Comparison by FBD and DBD - X -Direction

Figure 4.16 shows the variation of storey shear across the height of the building, by FBD and DBD.

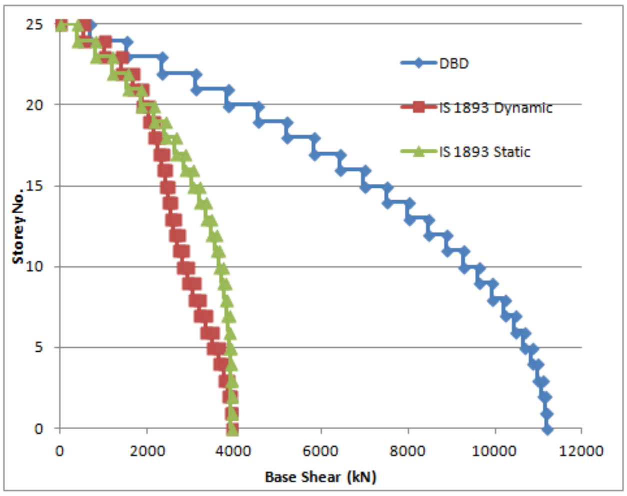

Figure 4.16: Variation of the Storey Shear across the height- X -Direction

Figure 4.17 shows the Overturning moment distribution across the height of the building.

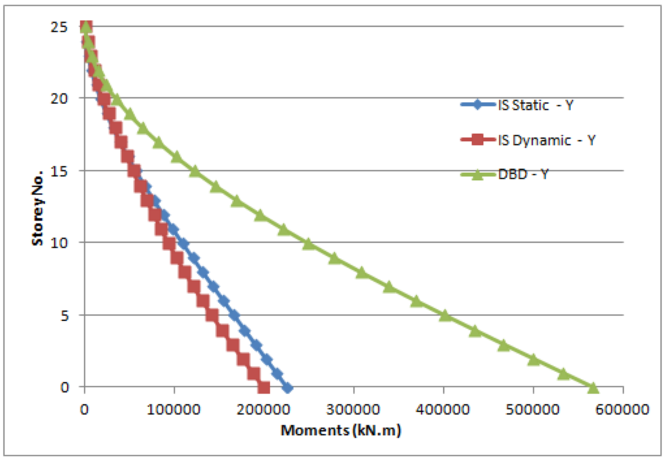

Figure 4.17: Overturning Moment Comparison - X -Direction

Y - DIRECTION

The plots for the Y - Direction are as follows:

Figure 4.18 shows the comparison of the displacement profile of the building by FBD and DBD.

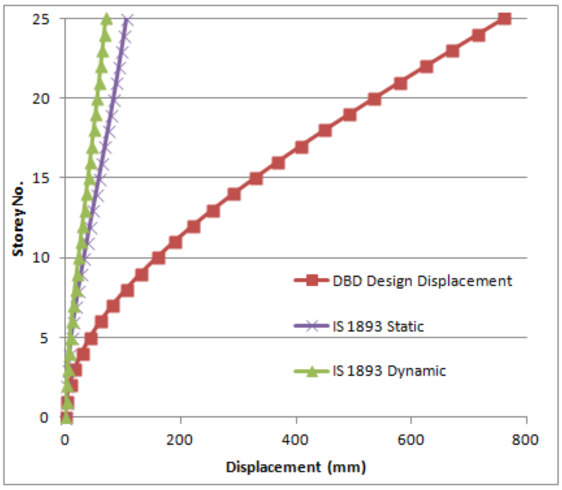

Figure 4.18: Displacement Comparison by FBD and DBD- Y -Direction

Figure 4.19 shows the comparison of drift of the building by FBD and DBD.

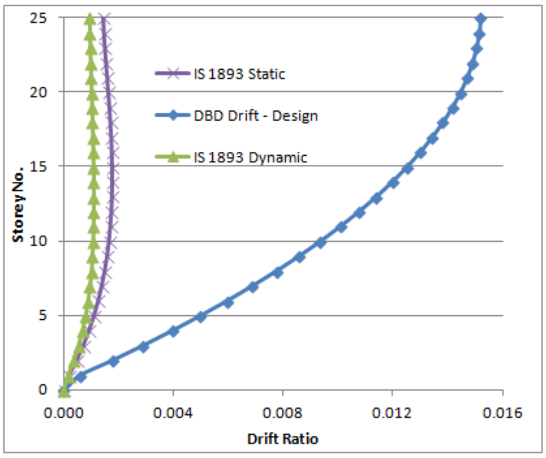

Figure 4.19: Drift Variation by FBD and DBD - Y -Direction

Figure 4.20 and Figure 4.21 shows the variation of the lateral forces and storey shear, respectively across the height of the building, by FBD and DBD.

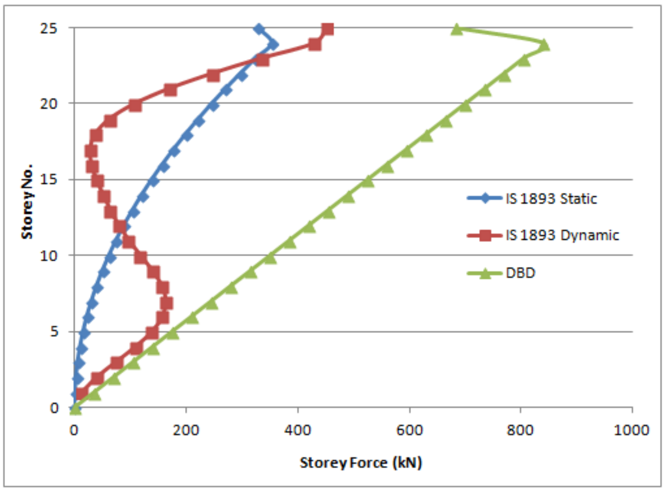

Figure 4.20: Lateral Forces Comparison by FBD and DBD - Y -Direction

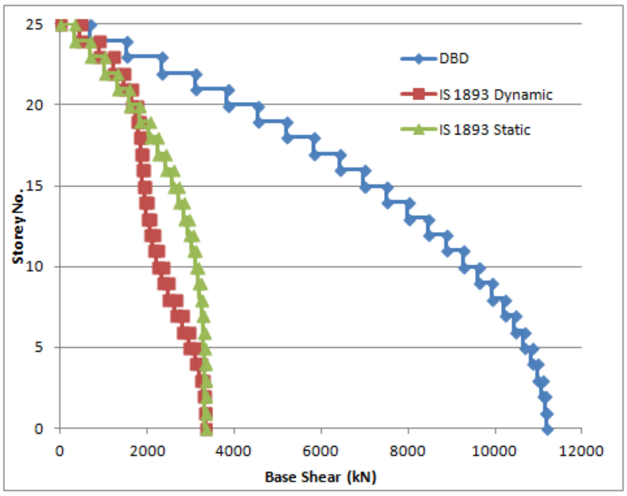

Figure 4.21: Variation of the Storey Shear across the height- Y - Direction

Figure 4.22 shows the Overturning moment distribution across the height of the building.

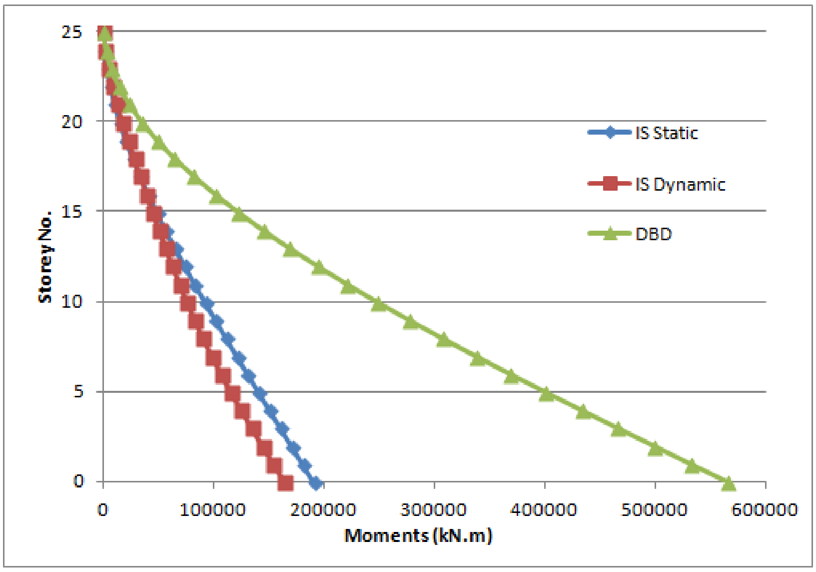

Figure 4.22: Overturning Moment Comparison - Y -Direction

Tables 4.2 and 4.3 shows the comparison between FBD and DBD for various parameters for two buildings, viz. 15 storeys and 25 storeys.

Table 4.4 and 4.5 highlights the effect of code drift limit imposed on the building and also the ductility demand and capacity of the building, for the two buildings, viz. 15 storeys and 25 storeys.

In DBD as compared to FBD, time period increases, ductility reduces, hence, base shear increases. When increasing from 15 to 25 storeys, the ratio of base shear of DBD by FBD remains nearly the same. Also, the ductiity capacity of the 15 storey building comes out to be higher than 25 storey building. The equivalent damping of both the building remains the same.

When performing DBD without considering code drift limits i.e. working on the capacity of the building, the stiffness reduces, design displacement increases, system damping increases, and base shear drastically reduces. **Hence, it can be concluded that because of the low limit of code-drift imposed on the structure and higher yield drift capacity of the building, the difference between this two drift value is small. Hence, the ductility demand is very low.**

Table 4.2: Comparison of FBD and DBD for 15 Storey building

Response Quantities	FBD @X (Static) - 15 Storeys	FBD @ X (Dynamic) - 15 Storeys	DBD @ X - 15 Storeys	FBD @Y (Static) - 15 Storeys	FBD @ Y (Dynamic) - 15 Storeys	DBD @ Y - 15 Storeys
Time Period, Te (sec)	0.81	1.3	2.14	0.95	1.3	2.14
Ductility	5.00	5.00	1.00	5.00	5.00	1
Base Shear, VB (kN)	3888	3895	10817	3297	3301	10817
Damping (%)	5.0	5.0	5	5.0	5.0	5.0

Table 4.3: Comparison of FBD and DBD for 25 Storey building

Response Quantities	FBD @X (Static) - 25 Storeys	FBD @ X (Dynamic) - 25 Storeys	DBD @ X - 25 Storeys	FBD @Y (Static) - 25 Storeys	FBD @ Y (Dynamic) - 25 Storeys	DBD @ Y - 25 Storeys
Time Period, Te (sec)	1.35	2.31	3.42	1.59	2.42	3.42
Ductility	5.00	5.00	1.00	5.00	5.00	1
Base Shear, VB (kN)	3923	3926	11156	3331	3331	11156
Damping (%)	5.0	5.0	5	5.0	5.0	5

Table 4.4: Comparison of DBD with and without Drift limit consideration for 15 Storey building

Response Quantities	DBD @ X - 15 Storeys	DBD @ X - 15 Storeys - No Code Drift	DBD @ Y - 15 Storeys	DBD @ Y - 15 Storeys - No Code Drift
Eff. Mass, me (kg)	4092961	4818924	4092961	4830309
Eff. Stiffness, ke(kN/m)	35213	2160	35213	2893
Design Disp. (mm)	307	1130	307	976
Total System Damping (%)	5	14.73	5	14.9
Base Shear, Vb (kN)	10817	2441	10817	2823
Ductility	1	3.22	1	3.34

Table 4.5: Comparison of DBD with and without Drift limit consideration for 25 Storey building

Response Quantities	DBD @ X - 25 Storeys	DBD @ X - 25 Storeys - No Code Drift	DBD @ Y - 25 Storeys	DBD @ Y - 25 Storeys - No Code Drift
Eff. Mass, me (kg)	6739151	7887626	6739151	7902030
Eff. Stiffness, ke(kN/m)	22748	624	22748	856
Design Disp. (mm)	490	2714	490	2315
Total System Damping (%)	5	14.1	5	14.23
Base Shear, Vb (kN)	11156	1694	11156	1982
Ductility	1	2.82	1	2.89

4.7 Summary

DBD for shear wall building is studied and carried out for a building having rectangular symmetric plan. For parametric study, two heights viz. 45 m (15 storeys) and 75 m (25 storeys) are taken into consideration and the variation in results is studied. Also, drift limit is ignored and the difference in required ductility (i.e the ductility demand) and the available ductility (i.e. the ductility capacity) is studied.

Chapter 5

Wall-Frame Building

5.1 Introduction

In a wall-frame structure, there is large stiffness variation between the frame and the wall which means that the walls will yield at significantly lower significantly lower lateral displacement than the frames. Hence, distribution of lateral force distribution between the walls and the frames based on the initial stiffness has little relevance to ductile response of the structure. The designer may choose the proportion of base shear force to be carried by the walls and the frames on the basis of experience and judgement rather than on elastic analysis based on the invalid estimates of wall and frame stiffness. Typically, the proportion of base shear to be carried by frames is from 15% to 50% of the total base shear. The substitute structure method is same as explained in the previous chapter, hence not explained here.

5.2 Problem Formulation

The building shown in Figure 5.1 is 15 storeys high. The building data is as given below:

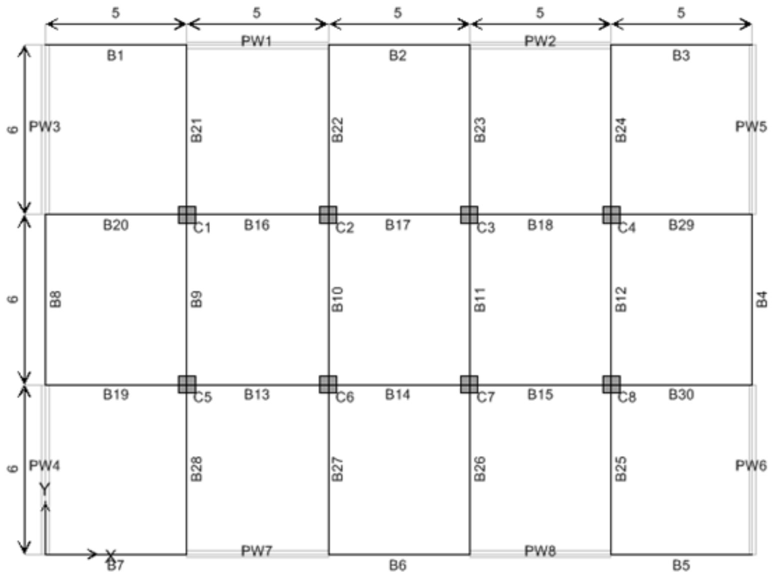

Figure 5.1: Plan of the Wall-frame building

Building Data:

Following parameters defines the building configuration:

No. Of storeys: 15

Storey height: 3m

Building height: 45m

Plan Dimensions: 25m x 18m

No. Of bays in X-Direction: 5

No. Of bays in Y-Direction: 3

Size of Beams: 300mm x 600mm

Size of Columns: 600mm x 600mm

Concrete Grade: M25

Steel Grade: Fe415

Earthquake Zone: Zone-V (Z=0.36)

Soil type: Medium

Thickness of Shear Walls: 250mm

Live Load = 3 kN/m^2 on all floors (including roof)

Live Load to considered for Seismic Analysis = 25% on Floors

= 0% on Roof

Importance Factor = 1

5.2.1 Load Calculation

The gravity as well as seismic weight calculations are as follows:

Shear Walls = 45 x 4 x [5 x 0.25 + 6 x 0.25] x 25 = 12375 kN

Floor Finish = 1 x 18 x 25 x 15 = 6750 kN

Beams Weight = 15 x [5 x 16 + 6 x 14] x 0.30x 0.60x 25 = 11070 kN

Columns weight = 45 x 8 x 0.6 x 0.6 x 25 = 3240 kN

Slab Weight = 0,15 x 25 x 15 x 18 x 25 = 25313 kN

Total Dead Load (DL) = 58748 kN

Total Live Load for Floors, except Roof = 3 x 18 x 25 x 14 = 18900 kN

Total Live Load for Roof = 3 x 18 x 25 = 1350 kN

Total Seismic Weight of the Building, We = 58748 + 0.25 x 18900 + 0 x 1350 - 3240/(2x 15) = 63365 kN

Seismic Wt of typical storey,

Wi = 58748/15 + 1350 x 0.25 = 4254 kN = 433640 kg

Seismic Wt of typical roof,

Wr = (58748 - 3240/2)/15 + 0 x 1350 = 3808.5 kN = 388230 kg

5.2.2 Force Based Design

The conventional FBD analysis has not included here as it is a standard procedure followed from IS 1893. For detailed calculations on FBD, refer Appendix B.

5.2.3 Displacement Based Design

The Displacement based design for the longitudinal direction i.e. X - Direction is explained step by step in this section. The Displacement based design for Y- direction is carried out the same way. Results are shown in the further sections.

STEP I. Design Choices

The β_F factor i.e the base shear proportion carried by frame of the total base shear is found to be 0.178 and 0.143 for X and Y directions respectively by FBD method of analysis using ETABS.

The first choice available to the designer is the proportion of the total base shear to be carried by the frame. The proportion V_F of the total base shear V_{BASE} to be carried by the frame is selected. Hence,

$$V_F = \beta_F \times V_{BASE} \; and \; V_W = (1 - \beta_F) \times V_{BASE} \tag{5.1}$$

where V_F and V_W are the base shear force carried by the frame and the wall respectively. The stiffness of the wall is comparatively much higher than of frames, hence the displacement response will be controlled by the stiffness of the walls. Hence, there is little danger of soft storey mechanism of the frame and there is much more freedom of choice available to the designer for the vertical distribution of the frame strength. Paulay has suggested the distribution of beam strength such that it results in constant frame shear at all levels. Fig 5.2 shows the distribution of the base shear force. This implies that the frames are essentially loaded by a single point load at the roof level, equal to V_F. This can be achieved by designing beams at all levels for equal strength except at the roof level where the strength should be half of the strength at other levels. The lateral forces carried by the walls are found by subtracting the frame lateral forces from the total lateral forces.

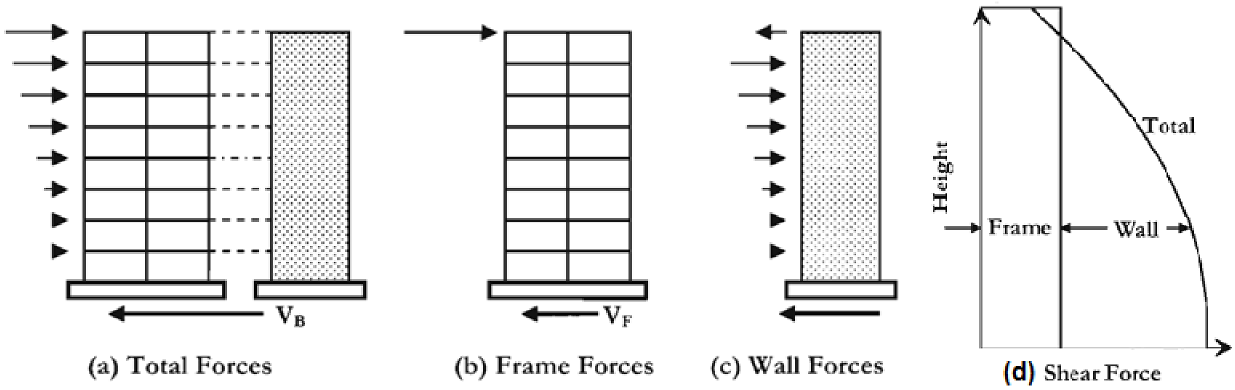

Figure 5.2: Distribution of Base shear force between Wall and Frame

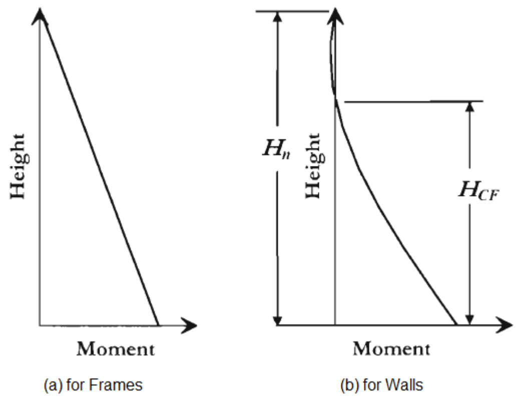

Figure 5.3: Moment Profile for (a) Frame and (b) Walls

Hence, the overturning moment (OTM) profile for the frame will be a straight line as for a cantilever beam subjected to a point load at its free end as shown in Figure 5.3(a). The vertical distribution of wall moments will be obtained by subtracting the frame moments from the total moment. The moment profile for the wall will be as shown in the

Figure 5.3(b). This implies a wall contraflexure point at height H_{CF} as shown in figure. This contraflexure height is important in determining the wall design displacements.

Let the proportion of base shear to be carried by the frame be 20% in the first iteration. Hence, $V_F = 0.2$

STEP II. Wall contraflexure height

To find the height of contraflexure, a unit base shear is distributed across the height of the building in triangular pattern as discussed before. Then the proportion of frame base shear is deducted from the total giving the base shear for walls. Using this base shear, overturning moment distribution is obtained.

The wall contraflexure height is the height at which the value of $M_{i,wall}$ in column 10 of the given below table 5.1 passes through zero, i.e. changes its sign from positive to negative.

Sample calculation of F_i :

F_{15} = 17470350 / 154066950 = 0.113 kN

From the column no. 10, the wall contraflexure point is between 12th and 13th storey i.e. between 36 m and 39 m. From linear interpolation, the wall contraflexure height comes out to be,

H_{CF} = 37.83 m

STEP III. Wall Yield displacements

The yield displacement profile of the wall frame structure is given by:

$$for Hi \leq H_{CF}, \Delta_{yi} = \phi_{yW}(Hi^2/2 - Hi^3/6H_{CF}) \tag{5.2}$$

$$for Hi > H_{CF}, \Delta_{yi} = \phi_{yW}(Hi \times H_{CF}/2 - H_{CF}^2/6) \tag{5.3}$$

Table 5.1: Preliminary Calculations to determine H_{CF}

Storey	**Height** H_i m	**Mass** m_i kg	m_i H_i kg.m	F_i kN	V_i kN	M_{OTMi} kN.m	$V_{i,frame}$ kN	$V_{i,wall}$ kN	$M_{i,wall}$ kN.m	$M_{i,frame}$ kN.m
15	45	388230	17470350	0.113	0.11	0	0.2	-0.09	0	0
14	42	433640	18212880	0.118	0.23	0.34	0.2	0.03	-0.26	0.6
13	39	433640	16911960	0.11	0.34	1.03	0.2	0.14	-0.17	1.2
12	36	433640	15611040	0.108	0.44	2.06	0.2	0.24	0.26	1.8
11	33	433640	14310120	0.09	0.54	3.38	0.2	0.34	0.98	2.4
10	30	433640	13009200	0.084	0.62	4.99	0.2	0.42	1.99	3
9	27	433640	11708280	0.076	0.7	6.84	0.2	0.5	3.24	3.6
8	24	433640	10407360	0.068	0.76	8.93	0.2	0.56	4.73	4.2
7	21	433640	9106440	0.059	0.82	11.22	0.2	0.62	6.42	4.8
6	18	433640	7805520	0.051	0.87	13.68	0.2	0.67	8.28	5.4
5	15	433640	6504600	0.042	0.92	16.3	0.2	0.72	10.3	6
4	12	433640	5203680	0.034	0.95	19.05	0.2	0.75	12.45	6.6
3	9	433640	3902760	0.025	0.97	21.89	0.2	0.77	14.69	7.2
2	6	433640	2601840	0.017	0.99	24.82	0.2	0.79	17.02	7.8
1	3	433640	1300920	0.008	1	27.79	0.2	0.8	19.39	8.4
0	0	0	0	0	1	30.79	0.2	0.8	21.79	9
Sum		6459190	154066950	1						

where ϕ_{yW} is the yield curvature at the wall base.

The reinforcement grade is Fe 415. Hence, fy= 415 MPa.

The expected yield strength of the reinforcing bar is

fye=1.1fy = 1.1 x 415 = 456.5 MPa

The yield strain of the reinforcement is given by:

ε_y = fye/E

where E = Modulus of Elasticity of Steel = 2x 10^5 MPa

Hence, ε_y = 456.6/(2x105) = 0.0022825

The yield curvature for rectangular wall sections is given by:

ϕ_{yw}= 2 x ε_y / lw = 2 x 0.0022825 / 5 = 0.000913 per m

For Hi $\leq$ 37.83 m, $\Delta_{yi} = \phi_{yw}$ $(Hi^2/2$ - $Hi^3/6H_{CF})$ = 0.000913x $[Hi^2/2$ - $Hi^3/(6$ x $37.83)]$

For Hi > 37.91 m, Δ_{yi}= ϕ_{yw} (H_{CF} x $Hi/2$ - $H_{CF}^2/6$) = 0.000913x [37.91 x Hi/2 - 37.832/6]

The above profile for yield displacement is listed in the given table 5.2:

Table 5.2: Displacement Profile Calculations

Storey	Height H_i (m)	Mass m_i (kg)	Δ_{yi} (m)	Δ_{di} (m)	$m_i.\Delta_{di}^2$	$m_i.\Delta_{di}$	$m_i.\Delta_{di}.H_i$	Ultimate Drift
15	45	348522	0.559	0.634	139945	220848	9938149	0.0189
14	42	382926	0.507	0.577	127453	220919	9278591	0.0189
13	39	382926	0.456	0.52	103614	199189	7768385	0.0189
12	36	382926	0.404	0.463	82249	177469	6388883	0.0188
11	33	382926	0.352	0.407	63473	155902	5144757	0.0184
10	30	382926	0.302	0.352	47407	134735	4042040	0.0179
9	27	382926	0.254	0.298	34068	114217	3083871	0.017
8	24	382926	0.207	0.247	23370	94600	2270393	0.0161
7	21	382926	0.164	0.199	15136	76131	1598754	0.0149
6	18	382926	0.124	0.154	9109	59061	1063106	0.0134
5	15	382926	0.089	0.114	4973	43640	654603	0.0118
4	12	382926	0.059	0.079	2369	30117	361406	0.0099
3	9	382926	0.034	0.049	917	18742	168678	0.0078
2	6	382926	1.6E-2	0.025	249	9764	58585	0.0055
1	3	382926	0.004	0.0089	31	3434	10301	0.003
0	0	0	0	0	0	0	0	0
Sum		5709480			654364	1558768	51830501	

STEP IV. Design Displacement Profile

It would be reasonable to assume that frame strain limits do not govern the design displacement profile. Hence, design displacements will either be limited by material strains in the wall plastic hinges, or more commonly by drift limitations. The drifts will be maximum at the contraflexure height H_{CF}.

In this, first material strains is considered, then checked if codal drift governs:

Wall Material Strains:

The design displacement profile is given by:

$$\Delta_{Di} = \Delta_{Yi} + (\phi_{ls} - \phi_{yW})L_P H_i \tag{5.4}$$

where where k and L_{SP} have their equations as per the previous chapter and L_P is the plastic hinge length given by the equation:

$$L_P = kH_{CF} + 0.1l_w + L_{SP} \tag{5.5}$$

The corresponding drift at the contraflexure height is

$$\theta_{CF} = \phi_{yW} H_{CF}/2 + (\phi_{ls} - \phi_{yw})L_P \tag{5.6}$$

where ϕ_{ls} is the limit state curvature of the wall.

With no information on the strain at the maximum stress level for the wall reinforcing steel, a conservative value of $\varepsilon_{su} = 0.10$ is used.

Hence, the damage control curvature is given by:

ϕ_{dc} = 0.072/lw =0.072/5 = 0.0144 per m

Plastic Hinge length is given by:

$$L_P = kH_{CF} + 0.1l_w + L_{SP} \tag{5.7}$$

Where k =0.2(fu/fy - 1) $\leq$ 0.08

From IS 1786 : 1985, fu = 485 MPa (minimum)

Therefore, k = 0.2 x (485/415 - 1) = 0.0337

Lsp = 0.022 x fye x dbl =0.022 x 456.5 x 20 = 200.86 mm, assuming 20 mm dia. bars as longitudinal reinforcement in the wall.

Hence, Plastic Hinge length is, Lp = 1.98 m

Check if the code based drift limit at H_{CF} is exceeded:

θ_{cf}= ϕ_{yw} x H_{CF} /2 + (ϕ_{dc} - ϕ_{yw})Lp

= 0.000913 x 37.83/2 + (0.0114 - 0.000913) x 1.98

θ_{cf} = 0.044 rad

This exceeds the code based drift limit of 0.004 x 5 = 0.02(Ductility factor = 5 for Wall-frame buildings as per IS 1893 (Part 1) :2002), hence code drift limit governs the wall design.

STEP V. Higher Mode Effects:

Due to higher mode effects on tall buildings, the shear and moments on the higher storeys gets amplified. This needs to be incorporated somehow in DBD as DBD is essentially based on the first inelastic mode response of the structure. Hence, the drift limits needs to be reduced to compensate for the higher mode effects by the factor ω_θ.

$$\omega_\theta = 1 - (n - 5)/100 \times (M_{OTM,F}/M_{OTM} + 0.25) \tag{5.8}$$

where $M_{OTM,F}$ = Total resisting moment provided by the frames at the base; and M_{OTM} = Total Overturning moment at the base.

This correction factor will have negligible influence for n $\leq$ 10.

As discussed above, the drift limits needs to be reduced to compensate for the higher mode effects.

ω_θ = 1 -(n - 5)/100 x ($M_{OTM,F}$ / M_{OTM} + 0.25)

where n = no. of storeys = 15,

$M_{OTM,F}$ = 9 kN.m per Unit Base shear force

And M_{OTM} = 30.81 kN.m per Unit Base shear force from the above table.

ω_θ = 1 - (15 - 5)/100 x (9/30.81 + 0.25) = 0.946

Hence, the reduced design drift is,

θ_c = 0.946 x 0.02 = 0.0189

The displacement profile is thus given by:

$\Delta_{Di} = \Delta_{Yi}$ + (θ_c - ϕ_{YW} x H_{CF} /2) x Hi

= Δ_{Yi} + (0.0189 - 0.000913 x 37.83 /2) x Hi

Therefore, $\Delta_{Di} = \Delta_{Yi}$ + 0.001631 x Hi

The corresponding design displacement profile is listed in column 5 of Table 5.2.

STEP VI. Design SDOF Displacement

From table 5.2, the design displacement of the SDOF substitute structure is given by:

$$\Delta_D = \frac{\sum_{i=1}^{n} m_i \times \Delta_i^2}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{5.9}$$

Δ_D = 653620/1557690

= 0.4196 m

STEP VII. Effective Height

From Table 5.2, the effective height is given by:

$$He = \frac{\sum_{i=1}^{n} m_i \times \Delta_i \times Hi}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{5.10}$$

Therefore, He = 5179947/1557690

= 33.25 m

STEP VIII. Equivalent Damping

The equivalent viscous damping to be used in the DBD will need to be a weighted average of the damping provided by the frames and by the walls, each of which have different ductility demands. Sullivan et al [15] have shown that for wall-frame the weighting should be related to the total base resisting moment provided by the different structural elements. The equivalent system damping to be used in design is thus,

$$\xi_{sys} = (\xi_W \times M_{OTM,W} + \xi_F \times M_{OTM,F})/(M_{OTM,W} + M_{OTM,F}) \quad (5.11)$$

where $\xi_F$and ξ_W are the damping ratios of the frames and walls respectively. This requires that the wall and frame ductility demands needs to be separately calculated.

The ductility demand for wall and frame is respectively given by

$$\mu_W = \Delta_D/\Delta_{YW} \quad (5.12)$$

$$and \ \ \mu_F = \Delta_D/(He \times \theta_{YF}) \quad (5.13)$$

where,

Δ_D = Design Displacement of SDOF system,

Δ_{YW} = Yield Displacement of Wall,

θ_{YF} = Frame yield drift

For calculating the equivalent damping of the system, the displacement ductility demands of walls and frames must first be calculated.

The yield displacement the SDOF substitute structure is calculated substituting He in above equation, since He < H_{CF}

$\Delta_{yi} = \phi_{yw}$ (He^2/2 - He^3 /6H_{CF})

= 0.000913x [33.25/2 - 33.25/(6 x 37.83)]

= 0.357 mm

The ductility of walls is:

$$\mu_W = \Delta_D/\Delta_{YW} \tag{5.14}$$

μ_W = 0.4196 / 0.357 = 1.18

The effective damping is given by:

ξ_W = 0.05 + 0.444 (μ_W -1)/ (μ_W x π) = 0.0711 = 7.11 %

For Frames:

The yield drift is given by

θ_{yF} = 0.5 x ε_Y x Lb / h_b

= 0.5 x 0.0022825 x 5 / 0.6

= 0.00951

Frame Displacement Ductility,

$$\mu_F = \Delta_D/(He \times \theta_{YF}) \tag{5.15}$$

μ_F = 0.4196/(33.25 x 0.00951) = 1.327

ξ_F = 0.05 + 0.565 (μ_W -1)/ (μ_W x π) = 0.0952 = 9.52 %

Finally, using unit base shear OTM (Over Turning Moment) values,

$$\xi_{sys} = (\xi_W \times M_{OTM,W} + \xi_F \times M_{OTM,F})/(M_{OTM,W} + M_{OTM,F}) \tag{5.16}$$

ξ_{sys} = (0.0711 x 21.81+0.0952 x 9)/30.81 = 0.0782 = 7.82%

The modification factor for this damping is found by linear interpolation using Table 3 of IS 1893 : 2002, shown in table 5.3 below.

Table 5.3: Modification for Damping

Damping	Modification Factor
7	0.9
10	0.8
7.82	0.873

Hence, the modification factor for damping is

m.f. = 0.873

STEP IX. Effective mass:

The Effective Mass of the SDOF system is given by

$$m_e = \frac{\sum_{i=1}^{n} m_i \times \Delta_i}{\Delta_d} \tag{5.17}$$

Hence, me = 1557690/ 0.4196

= 3712247 kg

STEP X. Base Shear:

The Base Shear of the SDOF system, using equation 4.3 is given by:

V_B = 2.255 x Z x me x m.f. x I / Δ_d

= 2.255 x 0.36 x 3712247 x 0.873 x 1 / 0.4196

= 6268 kN

STEP XI. Effective Stiffness:

The Effective Stiffness of the SDOF system is given by

$K_e = V_B$ / Δ_D = 6268 x 1000 / 0.4196 = 14938529 N/m

STEP XII. Effective Time Period:

The Effective Time Period of the SDOF system is given by

$T_e = 2\pi$ x $\sqrt{me/ke}$

$=$ 2 x 3.14 x $\sqrt{3712247/14938529}$

$=$ 3.13 seconds

STEP XIII. Force Distribution:

This can be obtained using table 5.1 as the distribution has already been done for base shear of 1 kN. For getting the actual values, this values are to be multiplied by the actual total base shear of 6268 kN.

Frame:

Base Shear carried by the Frames, V_F =0.2 x 6268 = 1254 kN

Base Moment carried by the walls, M_F = 9 x 6268 = 56412 kN.m

Walls:

Base Shear carried by the walls, V_W = (1-0.2) x 6268 = 5014 kN

Base Moment carried by the walls, M_W = 21.814 x 6268 = 136730 kN.m

5.3 Parametric Study

Parametric study is carried out by performing the DBD for 15 storey building with respect to different base shear proportion to be carried by the frame viz. 0.2, 0.3 and 0.4 and the results are presented in the subsequent sections. Also, two cases are taken, one in which the codal drift limit is considered and other in which the codal drift limit is ignored. The former is a traditional approach, while the latter is done only to know the ductility capacity of the building.

5.4 Results and Discussions

The DBD is carried out for the wall-frame building as mentioned earlier. The following section shows the plots of Displacement Comparison, Lateral Force Distribution, Base

Shear and Drift Ratio and Overturning Moment distribution between frame and wall as per DBD method. Also, meinforcement for selected columns has been tabulated in this section. The comparison of moments, displacements, shear force and lateral forces, etc have been presented in the form of plots for $\beta_F = 0.2$, 0.3 and 0.4 as follows:

5.4.1 Plots for $\beta_F = 0.2$

The plots showing the comparison of FBD and DBD for 15 storey building for frame base shear contribution of 20% for the X and Y directions are shown in this section.

FOR X-DIRECTION

The plots for the X - Direction are as follows:

Figure 5.4 shows the displacement profiles for FBD and DBD. While Figure 5.5 gives the comparison of drift variation across the height of the structure by FBD and DBD. The displacements and the drift is very high in DBD as compared to FBD. The yield and design displacement in DBD are very close to each other, hence the ductility demand is low.

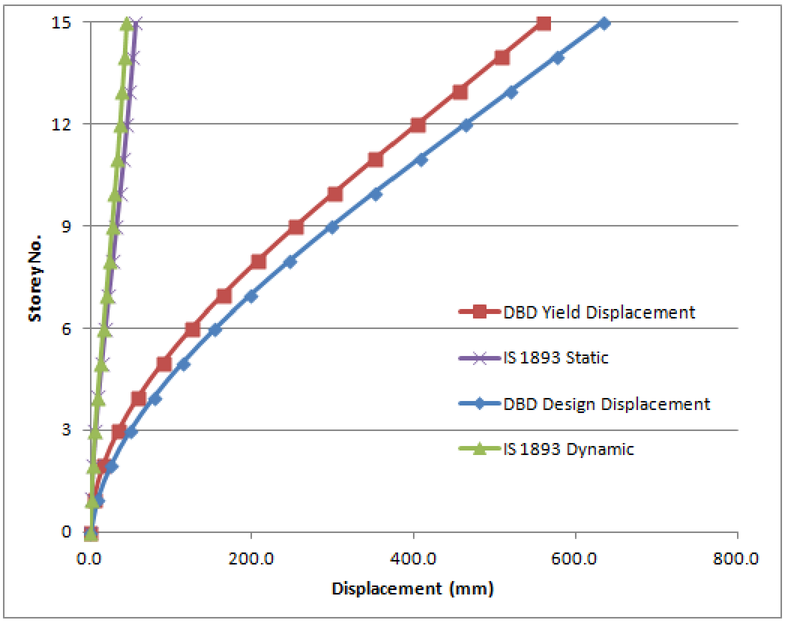

Figure 5.4: Displacement Comparison among FBD and DBD - X Direction -$\beta_F = 0.2$

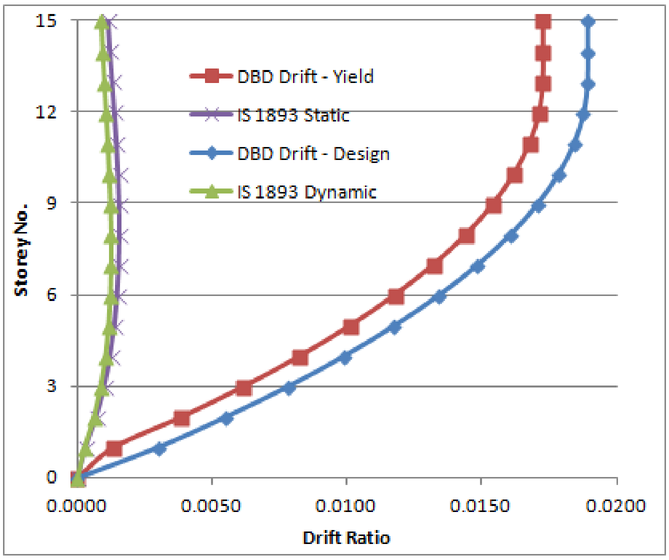

Figure 5.5: Drift Comparison among FBD and DBD - X Direction -$\beta_F = 0.2$

Figure 5.6 gives the comparison of lateral forces across the height of the structure by FBD and DBD. Upto 3 storeys, the storey forces in DBD are similar to FBD Dynamic and higher than FBD static. Beyond 3 storeys, they are quite high as compared to both- FBD static as well as Dynamic.

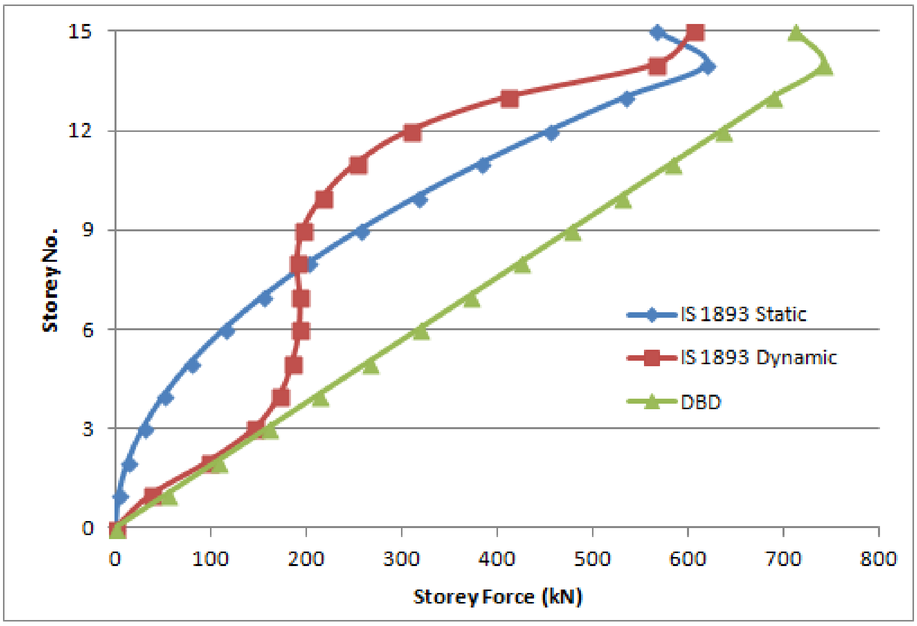

Figure 5.6: Lateral Forces Comparison among FBD and DBD- X Direction - $\beta_F = 0.2$

Figure 5.7 gives the storey shear profile across the height of the structure by FBD and DBD. The difference in storey shear between FBD and DBD goes on increasing with the decrease in height of the building.

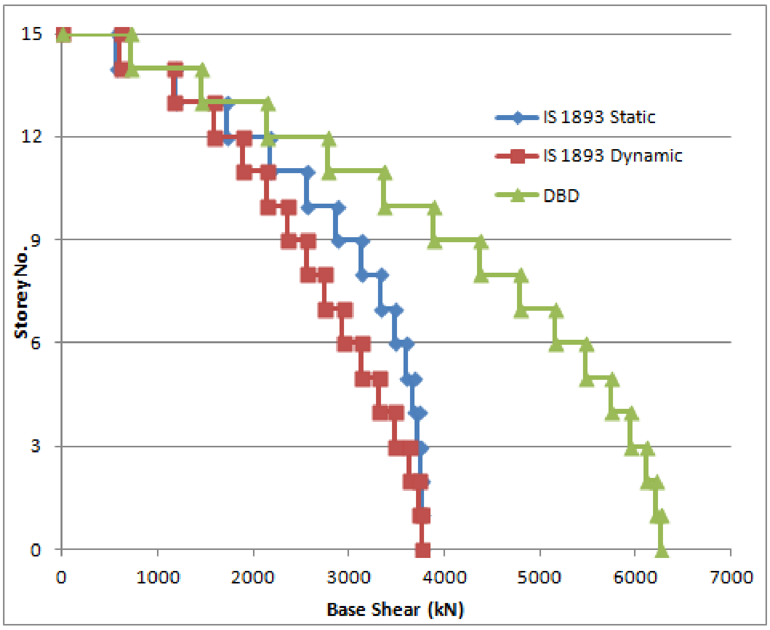

Figure 5.7: Storey Shear Comparison among FBD and DBD - X Direction - $\beta_F = 0.2$

Figure 5.8 gives the overturning moment distribution among wall and frame as per DBD across the height of the building. The moment profile of wall and frame is conforming to that as discussed before.

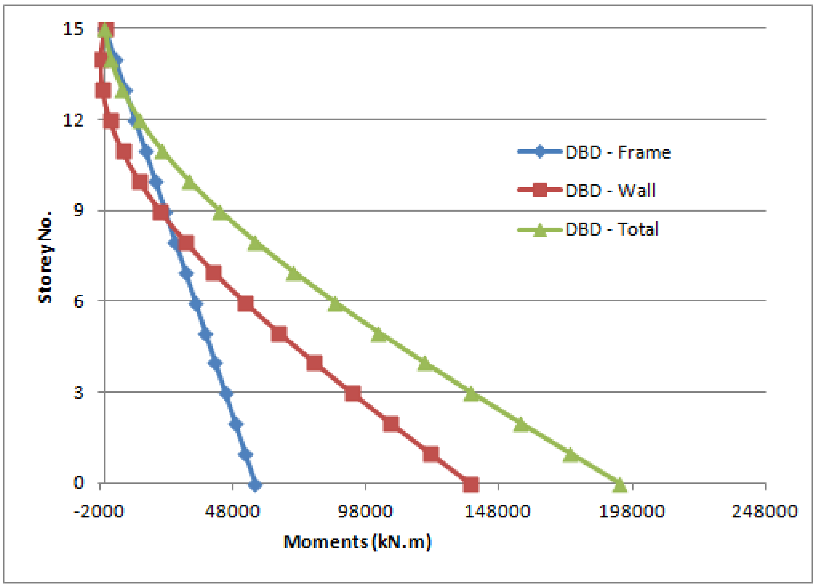

Figure 5.8: Overturning Moment Distribution for DBD - X Direction - $\beta_F = 0.2$

Figure 5.9 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

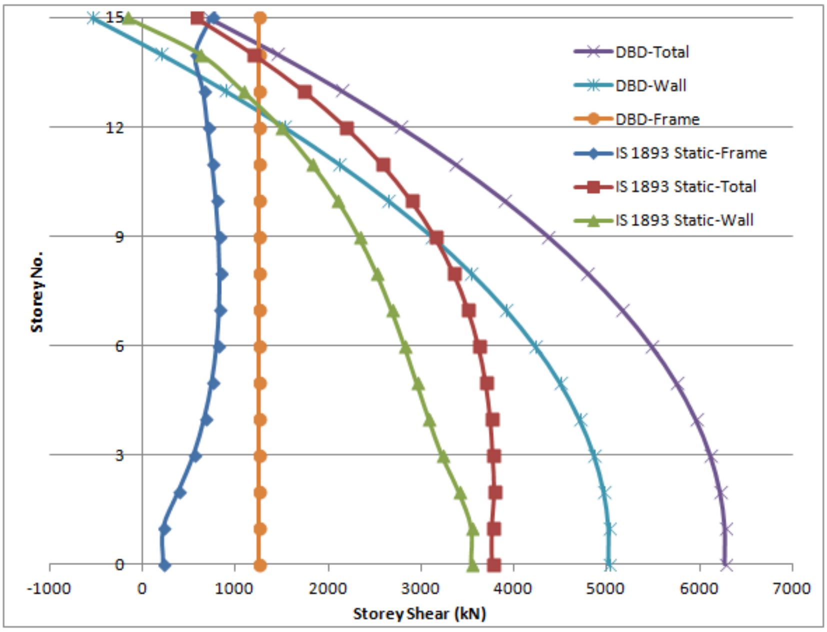

Figure 5.9: Storey Shear Distribution between Frames and Walls by FBD and DBD - X Direction -$\beta_F = 0.2$

Y - DIRECTION

The plots for the Y - Direction are as follows:

Figure 5.10 shows the displacement profiles for FBD and DBD. While Figure 5.11 gives the comparison of drift variation across the height of the structure by FBD and DBD.

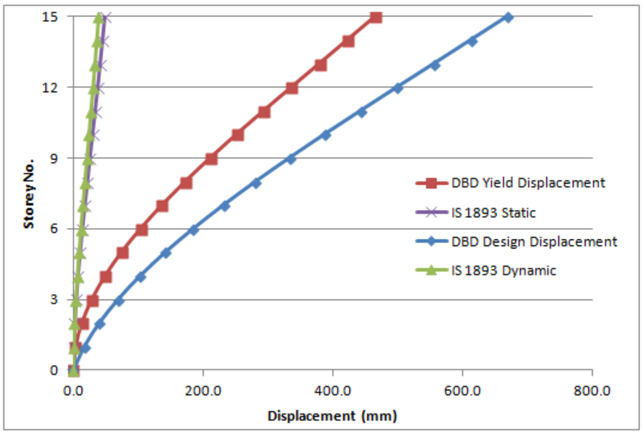

Figure 5.10: Displacement Comparison among FBD and DBD- Y-Direction-$\beta_F = 0.2$

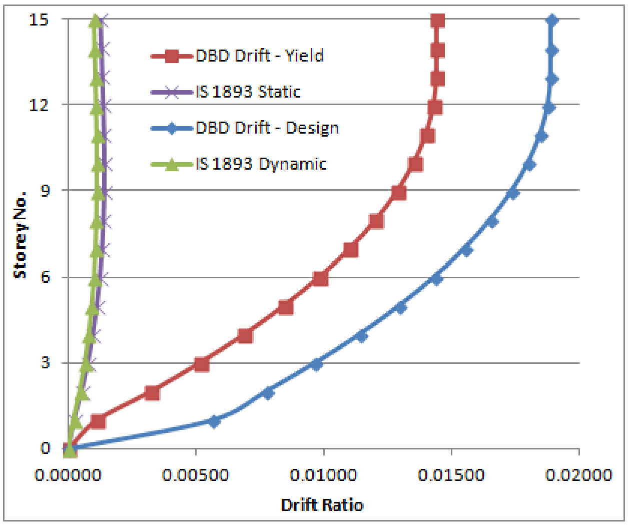

Figure 5.11: Drift Comparison among FBD and DBD - Y Direction -$\beta_F = 0.2$

Figure 5.12 gives the comparison of lateral forces across the height of the structure by FBD and DBD.

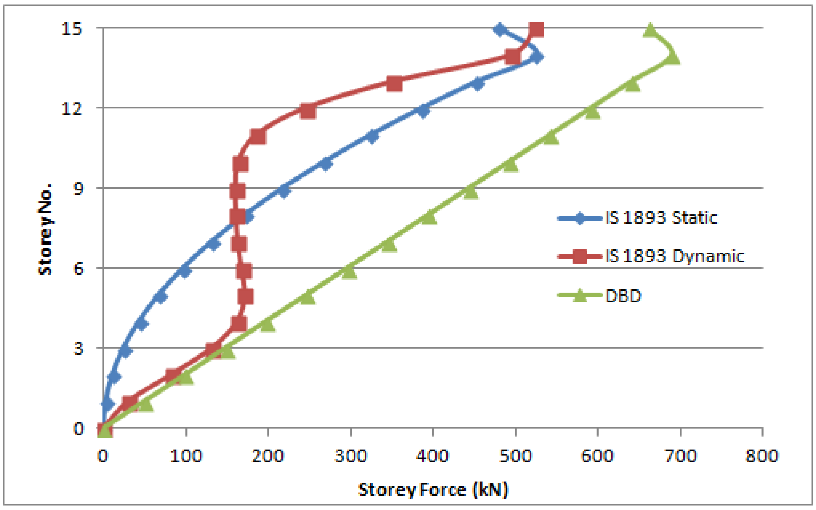

Figure 5.12: Lateral Forces Comparison among FBD and DBD- Y Direction - $\beta_F = 0.2$

Figure 5.13 gives the base shear profile across the height of the structure by FBD and DBD.

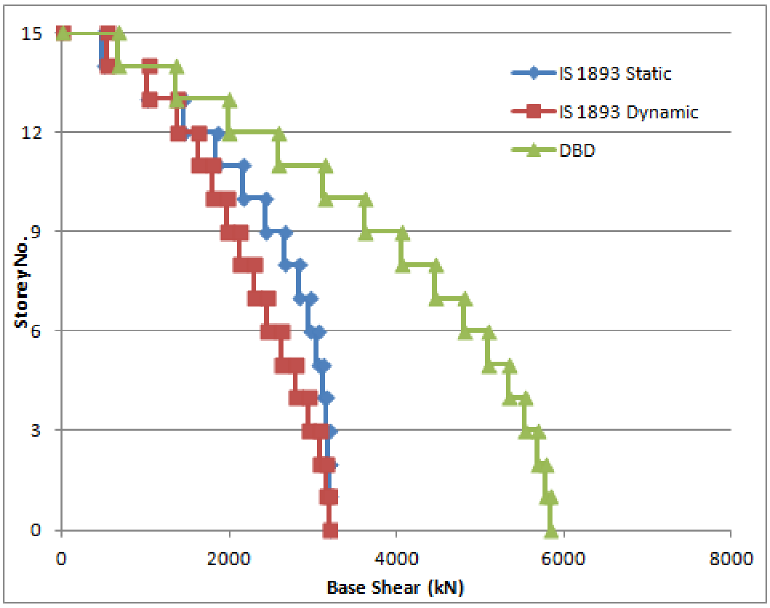

Figure 5.13: Storey Shear Comparison among FBD and DBD - Y Direction - $\beta_F = 0.2$

Figure 5.14 gives the overturning moment distribution among wall and frame as per DBD across the height of the building.

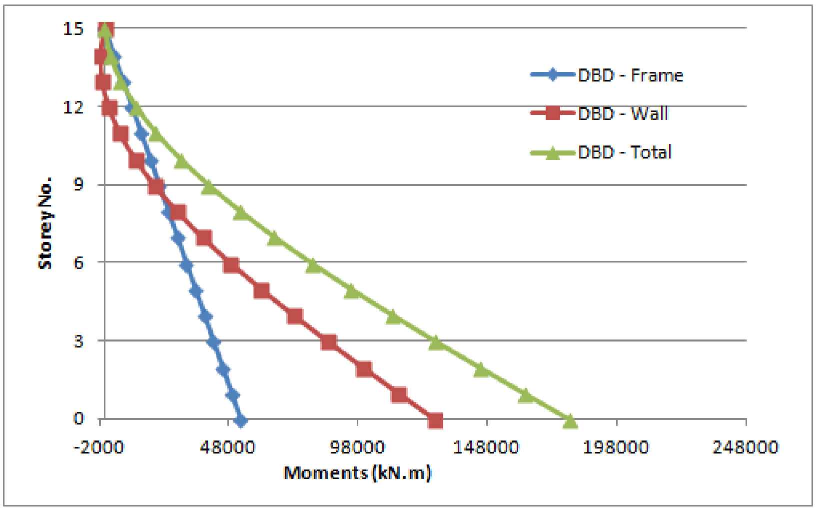

Figure 5.14: Overturning Moment Distribution for DBD - Y Direction - $\beta_F = 0.2$

Figure 5.15 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

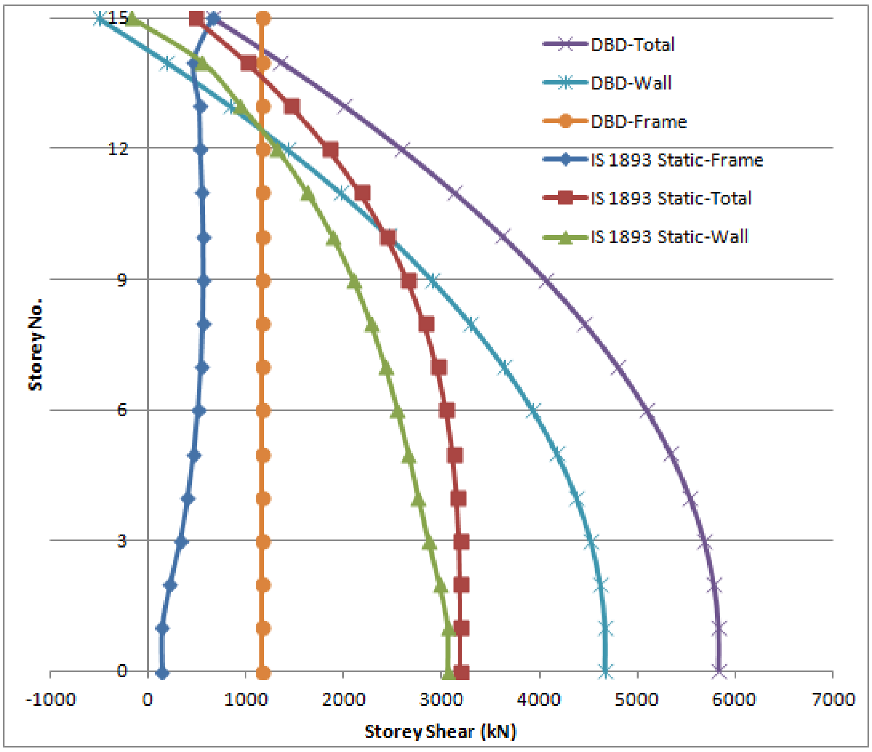

Figure 5.15: Storey Shear Distribution between Frames and Walls by FBD and DBD - Y Direction -$\beta_F = 0.2$

5.4.2 Plots for $\beta_F = 0.3$

The plots showing the comparison of FBD and DBD for 15 storey building for frame base shear contribution of 30% for the X and Y directions are shown in this section.

X DIRECTION

The plots for the X - Direction are as follows:

Figure 5.16 shows the displacement profiles for FBD and DBD. While Figure 5.17 gives the comparison of drift variation across the height of the structure by FBD and DBD.

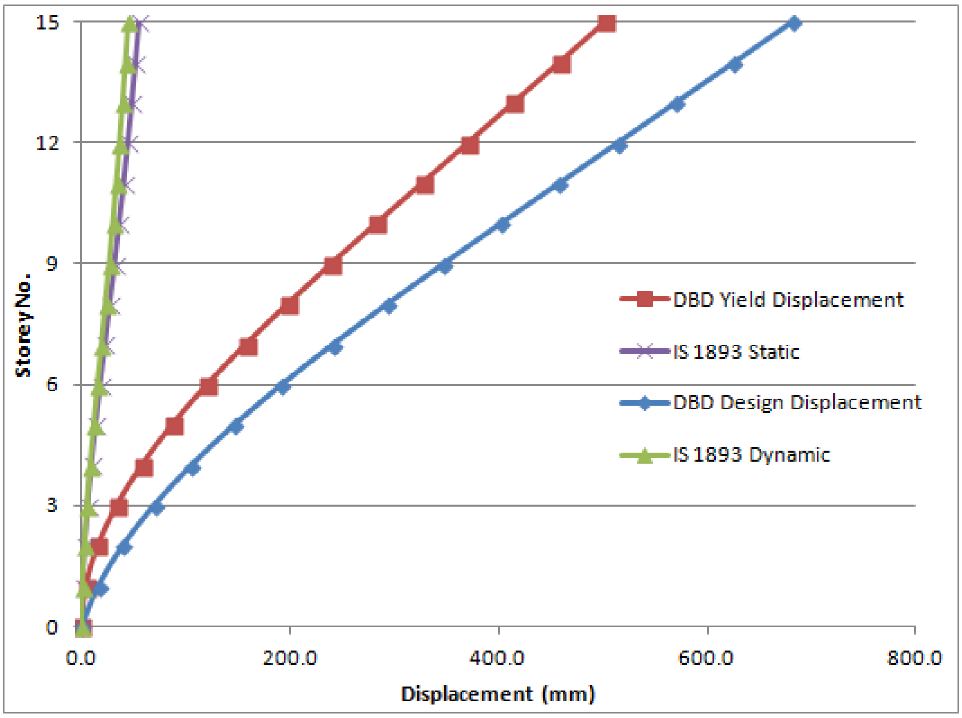

Figure 5.16: Displacement Comparison among FBD and DBD - X Direction -β_F = 0.3

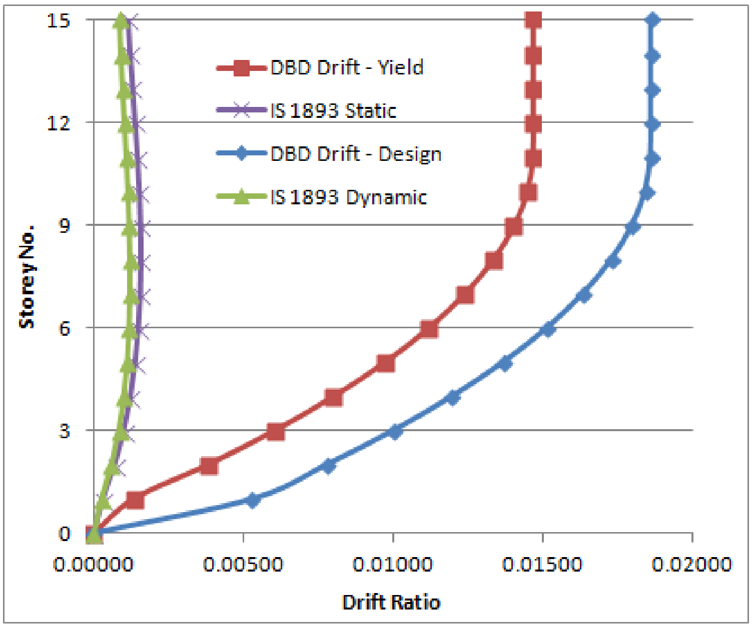

Figure 5.17: Drift Comparison among FBD and DBD - X Direction -$\beta_F = 0.3$

Figure 5.18 gives the comparison of lateral forces across the height of the structure by FBD and DBD.

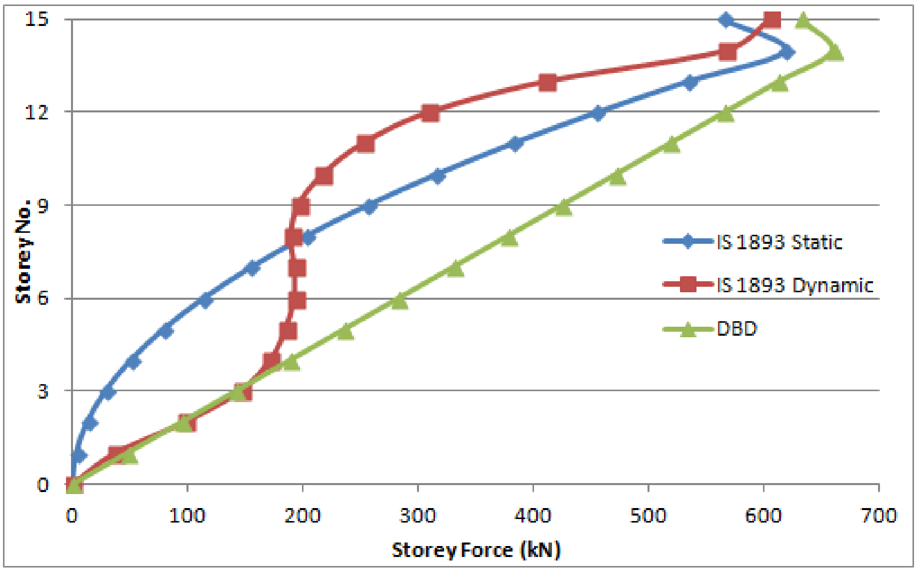

Figure 5.18: Lateral Forces Comparison among FBD and DBD- X Direction - $\beta_F =$ 0.3

Figure 5.19 gives the base shear profile across the height of the structure by FBD and DBD.

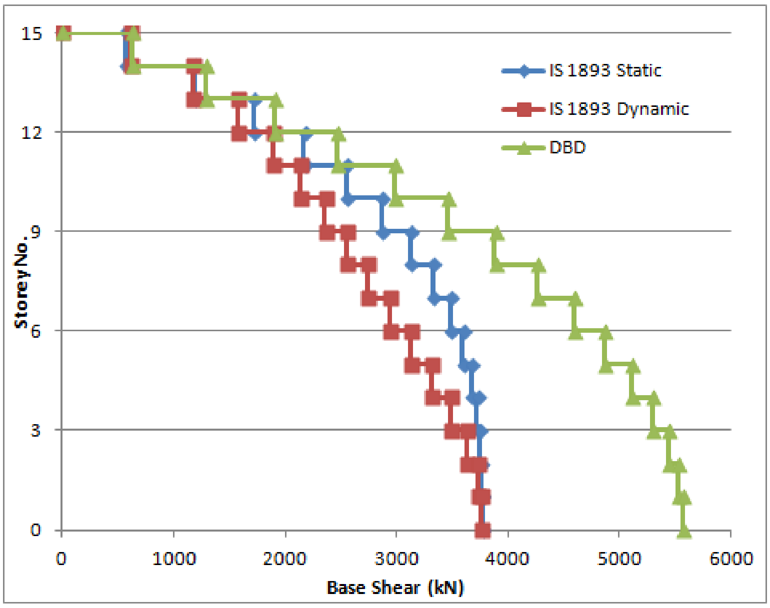

Figure 5.19: Storey Shear Comparison among FBD and DBD - X Direction - $\beta_F = 0.3$

Figure 5.20 gives the overturning moment distribution among wall and frame as per DBD across the height of the building.

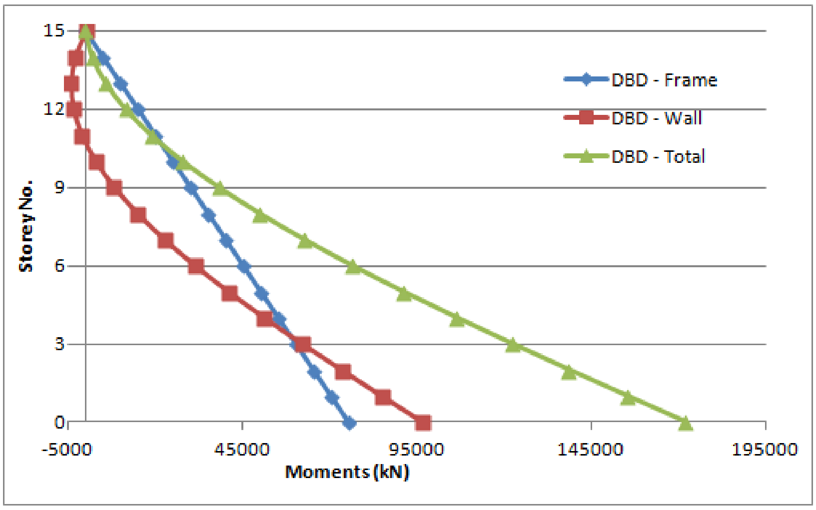

Figure 5.20: Overturning Moment Distribution for DBD - X - $\beta_F = 0.3$

Figure 5.21 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

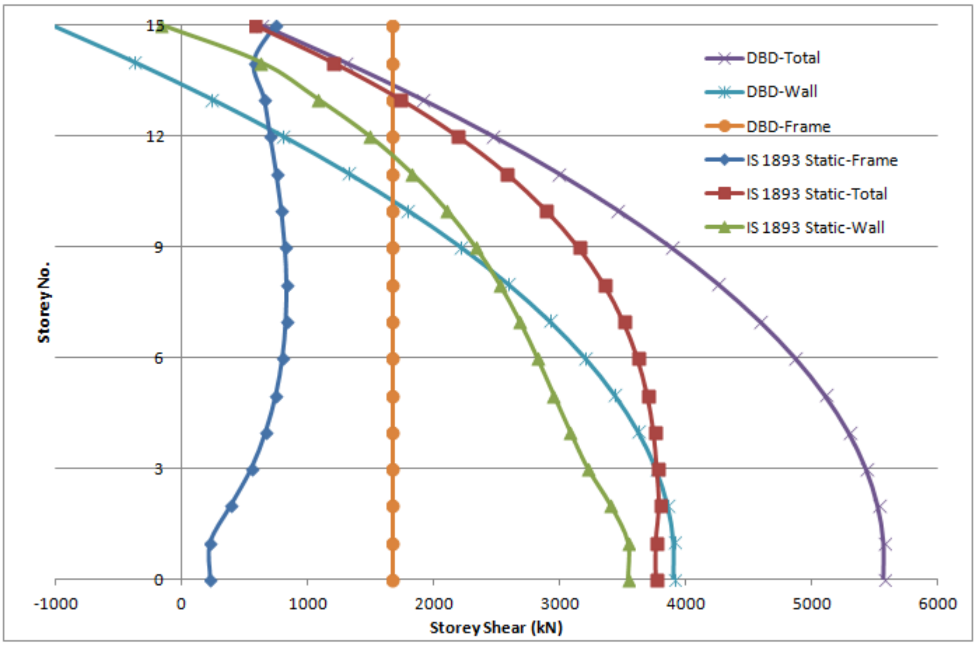

Figure 5.21: Storey Shear Distribution between Frames and Walls by FBD and DBD - X Direction -$\beta_F = 0.3$

Y DIRECTION

The plots for the Y - Direction are as follows:

Figure 5.22 shows the displacement profiles for FBD and DBD. While Figure 5.23 gives the comparison of drift variation across the height of the structure by FBD and DBD.

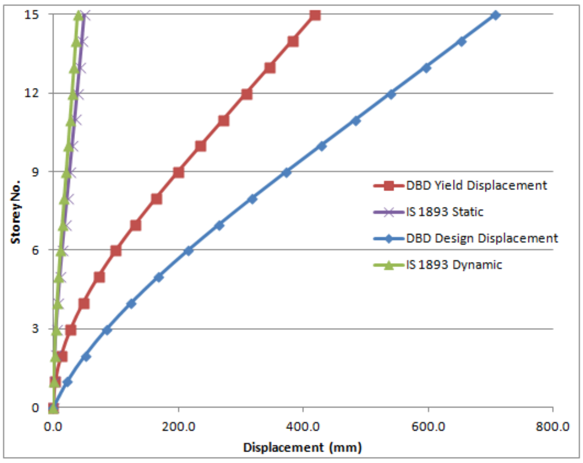

Figure 5.22: Displacement Comparison among FBD and DBD - Y-Direction-β_F=0.3

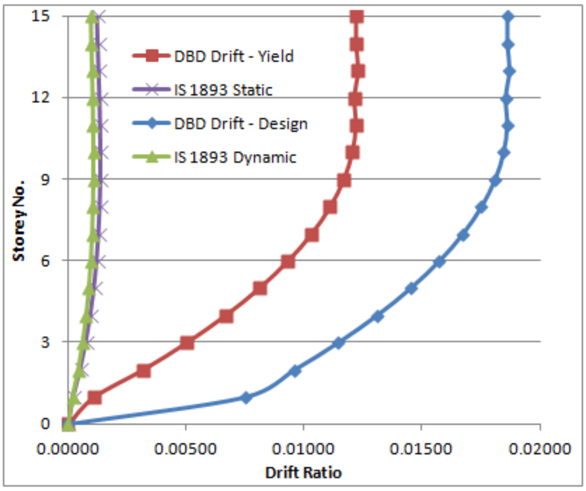

Figure 5.23: Drift Comparison among FBD and DBD - Y Direction -β_F = 0.3

Figure 5.24 gives the comparison of lateral forces across the height of the structure by FBD and DBD.

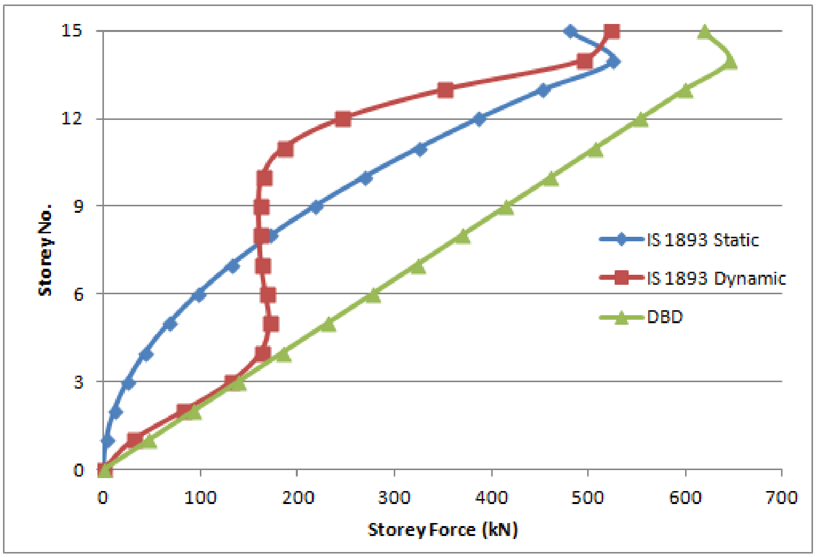

Figure 5.24: Lateral Forces Comparison among FBD and DBD- Y Direction - $\beta_F = 0.3$

Figure 5.25 gives the base shear profile across the height of the structure by FBD and DBD.

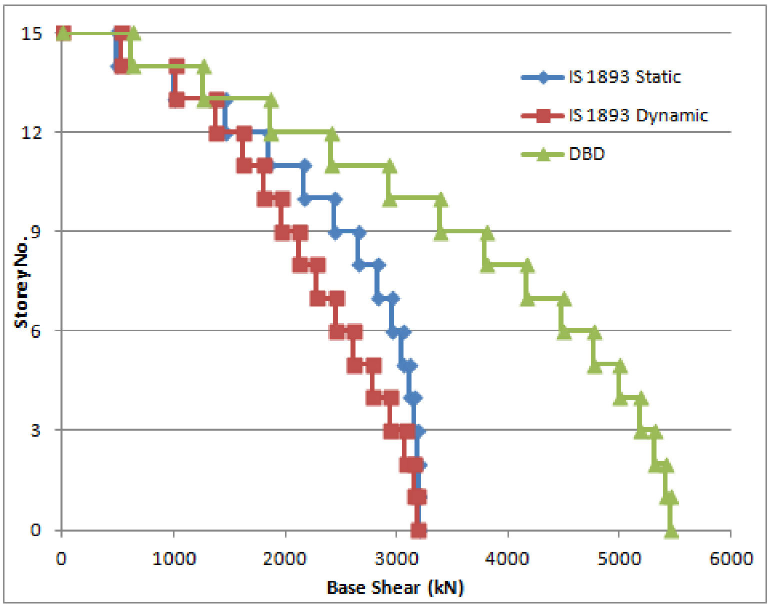

Figure 5.25: Storey Shear Comparison among FBD and DBD - Y Direction - $\beta_F = 0.3$

Figure 5.26 gives the overturning moment distribution among wall and frame as per DBD across the height of the building.

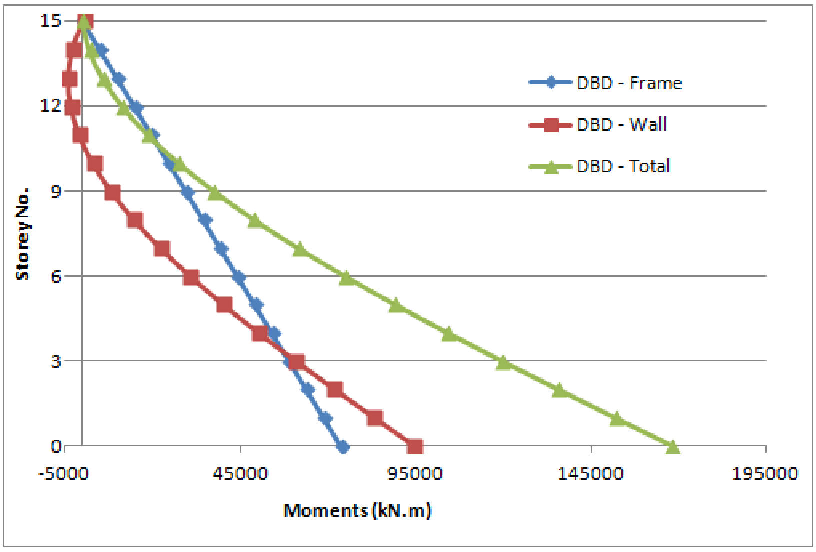

Figure 5.26: Overturning Moment Distribution for DBD - Y Direction - $\beta_F = 0.3$

Figure 5.27 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

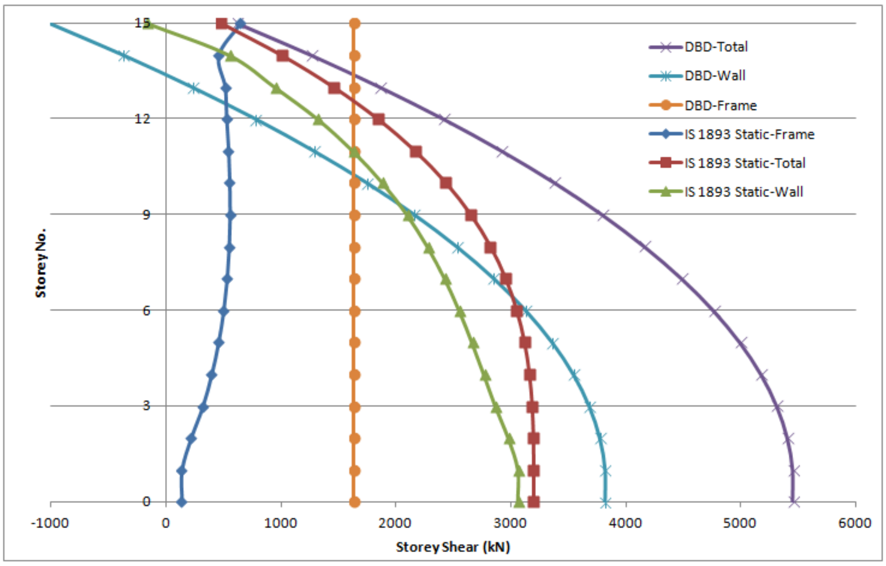

Figure 5.27: Storey Shear Distribution between Frames and Walls by FBD and DBD - Y Direction -$\beta_F = 0.3$

5.4.3 Plots for $\beta_F = 0.4$

The plots showing the comparison of FBD and DBD for 15 storey building for frame base shear contribution of 40% for the X and Y directions are shown in this section.

X DIRECTION

The plots for the X - Direction are as follows:

Figure 5.28 shows the displacement profiles for FBD and DBD. While Figure 5.29 gives the comparison of drift variation across the height of the structure by FBD and DBD.

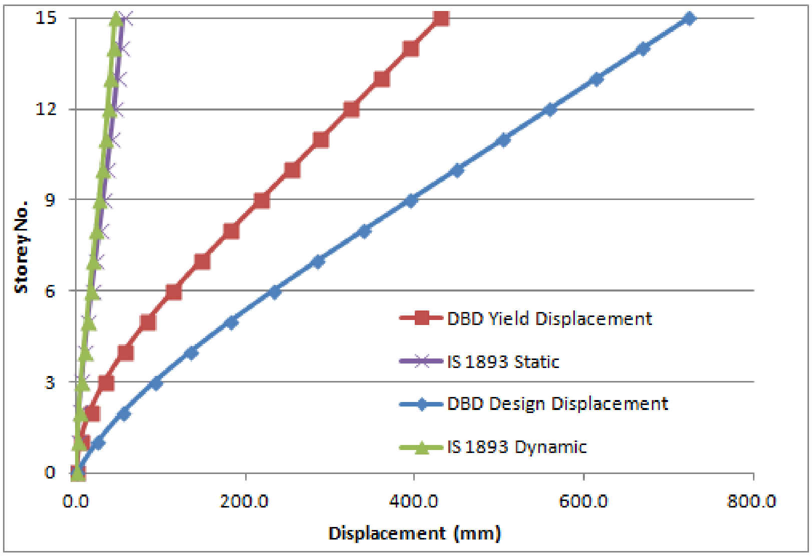

Figure 5.28: Displacement Comparison among FBD and DBD - X Direction -β_F = 0.4

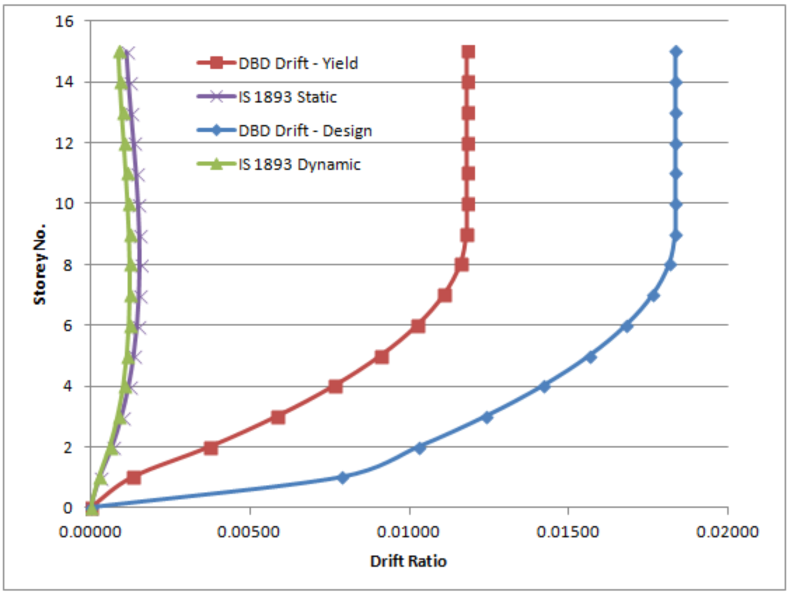

Figure 5.29: Drift Comparison among FBD and DBD - X Direction -β_F = 0.4

Figure 5.30 gives the comparison of lateral forces across the height of the structure by FBD and DBD.

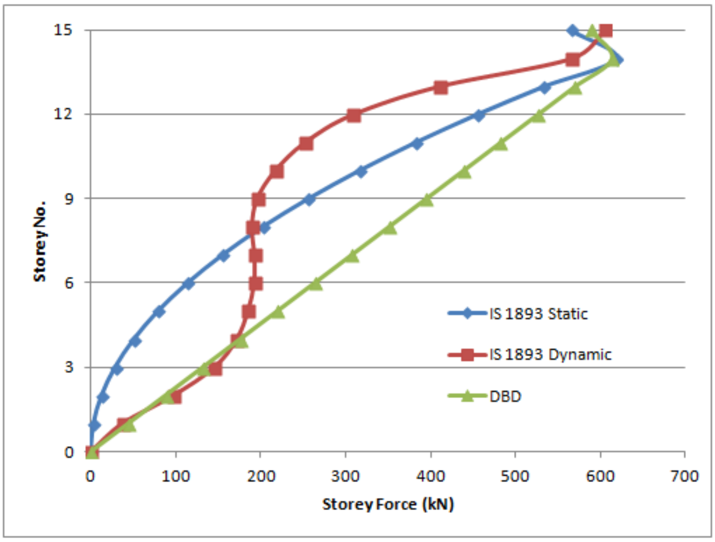

Figure 5.30: Lateral Forces Comparison among FBD and DBD- X Direction - β_F = 0.4

Figure 5.31 gives the base shear profile across the height of the structure by FBD and DBD.

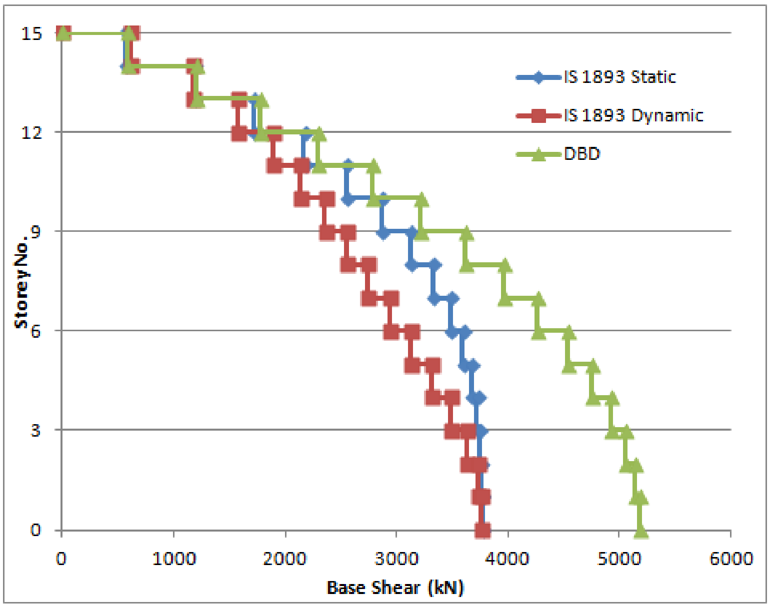

Figure 5.31: Storey Shear Comparison among FBD and DBD - X Direction - $\beta_F = 0.4$

Figure 5.32 gives the overturning moment distribution among wall and frame as per DBD across the height of the building.

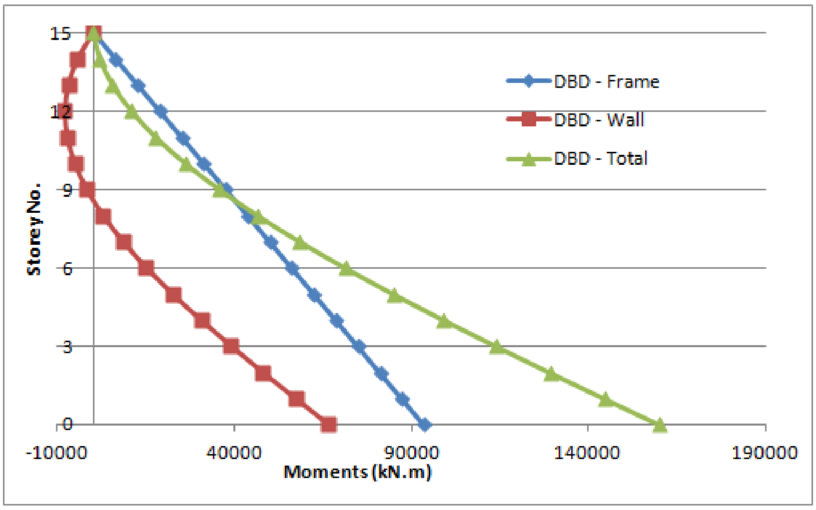

Figure 5.32: Overturning Moment Distribution for DBD - X Direction - $\beta_F = 0.4$

Figure 5.33 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

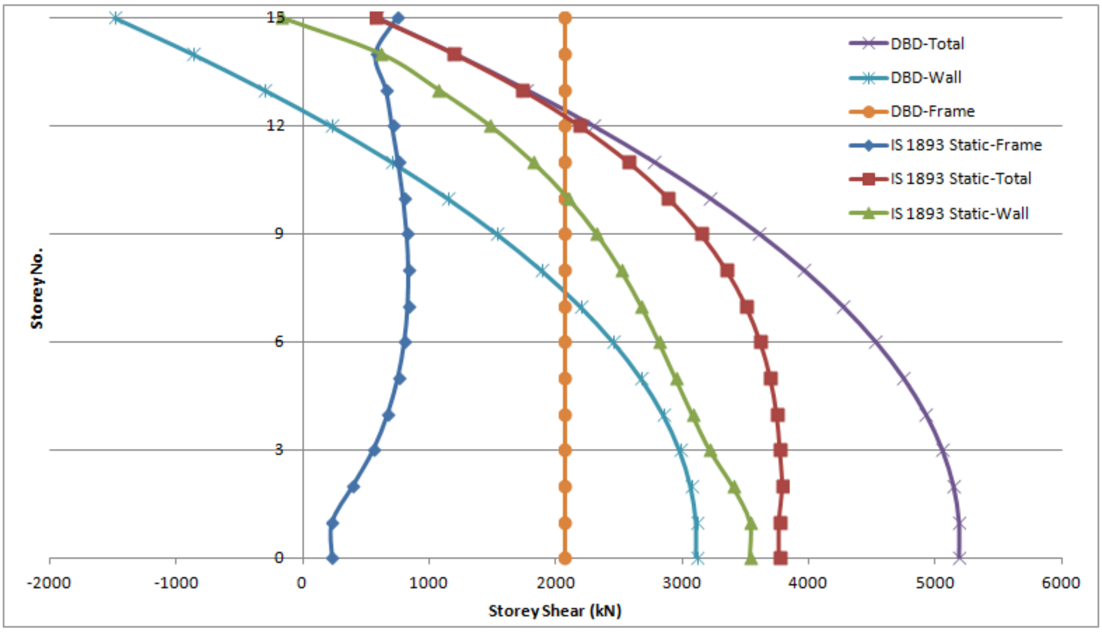

Figure 5.33: Storey Shear Distribution between Frames and Walls by FBD and DBD - X Direction -$\beta_F = 0.4$

Y DIRECTION

The plots for the Y - Direction are as follows:

Figure 5.34 shows the displacement profiles for FBD and DBD. While Figure 5.35 gives the comparison of drift variation across the height of the structure by FBD and DBD.

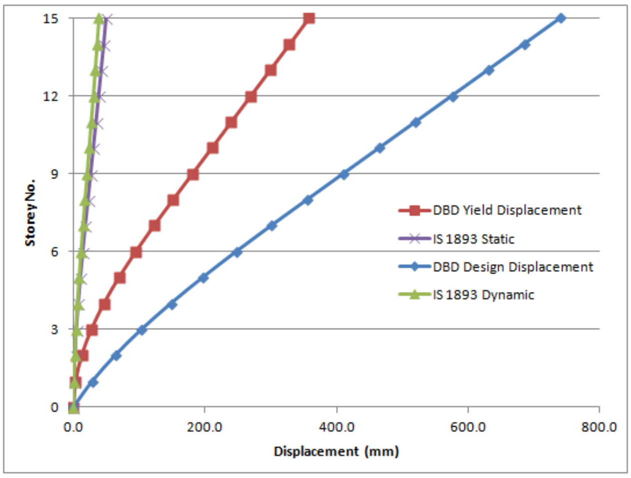

Figure 5.34: Displacement Comparison among FBD and DBD - Y-Direction -β_F=0.4

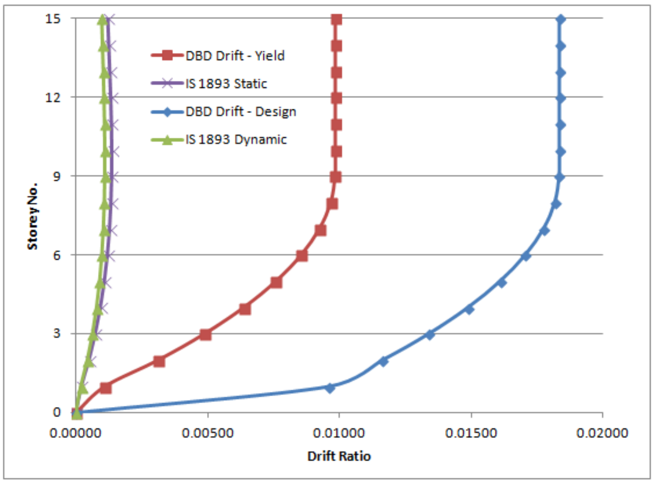

Figure 5.35: Drift Comparison among FBD and DBD - Y Direction -β_F = 0.4

Figure 5.36 gives the comparison of lateral forces across the height of the structure by FBD and DBD.

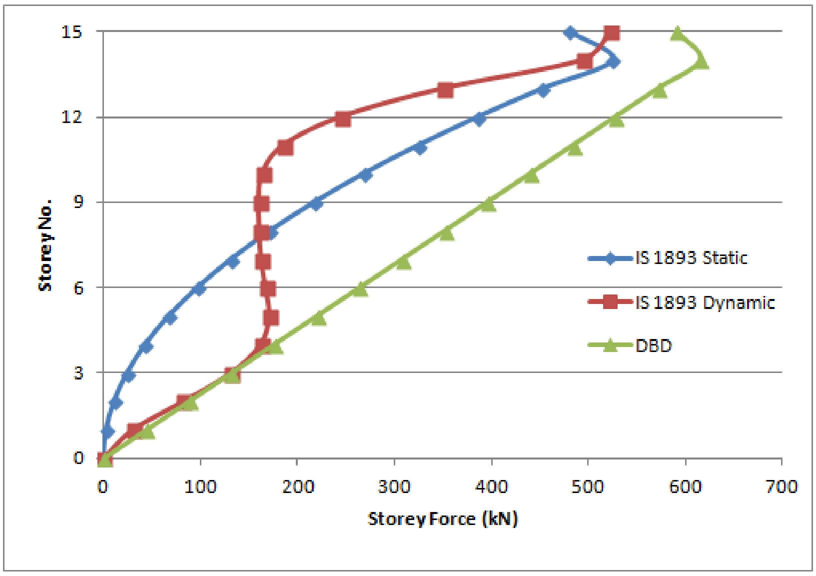

Figure 5.36: Lateral Forces Comparison among FBD and DBD- Y Direction - $\beta_F = 0.4$

Figure 5.37 gives the base shear profile across the height of the structure by FBD and DBD.

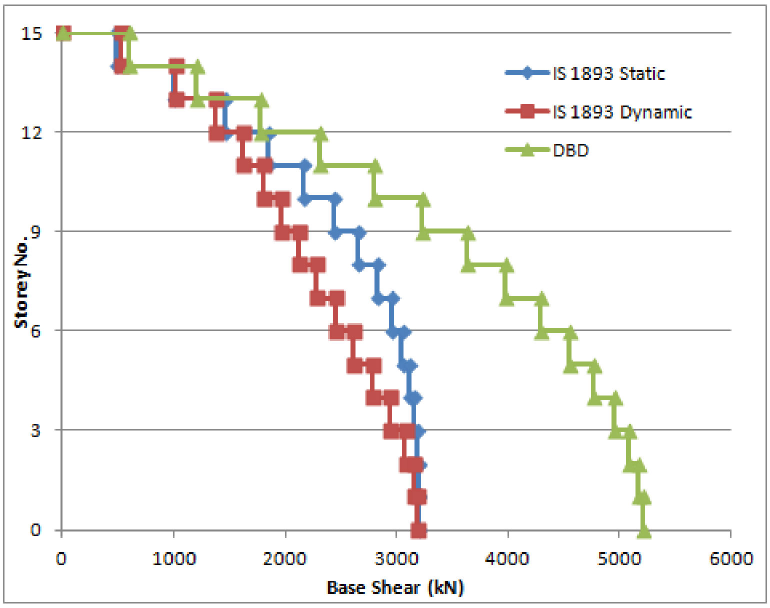

Figure 5.37: Storey Shear Comparison among FBD and DBD - Y Direction - $\beta_F = 0.4$

Figure 5.38 gives the overturning moment distribution among wall and frame as per DBD across the height of the building.

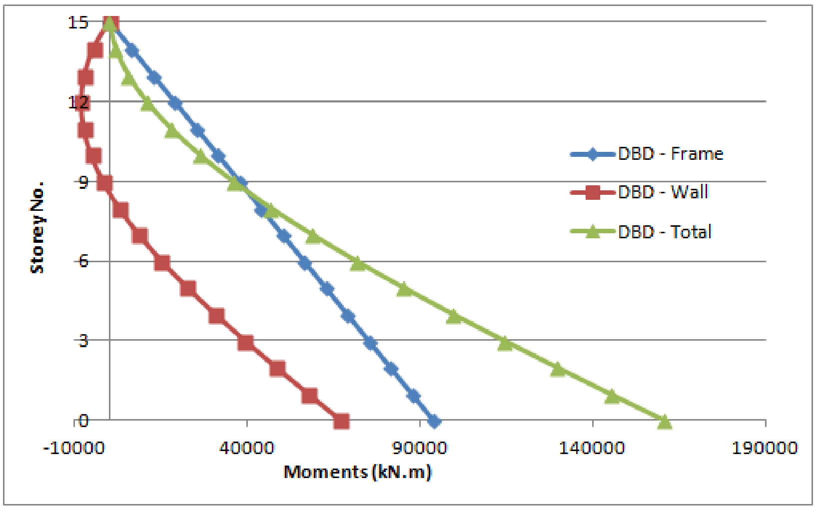

Figure 5.38: Overturning Moment Distribution for DBD - Y Direction - $\beta_F = 0.4$

Figure 5.39 shows the storey shear distribution across the frame and wall component of the building as per FBD and DBD.

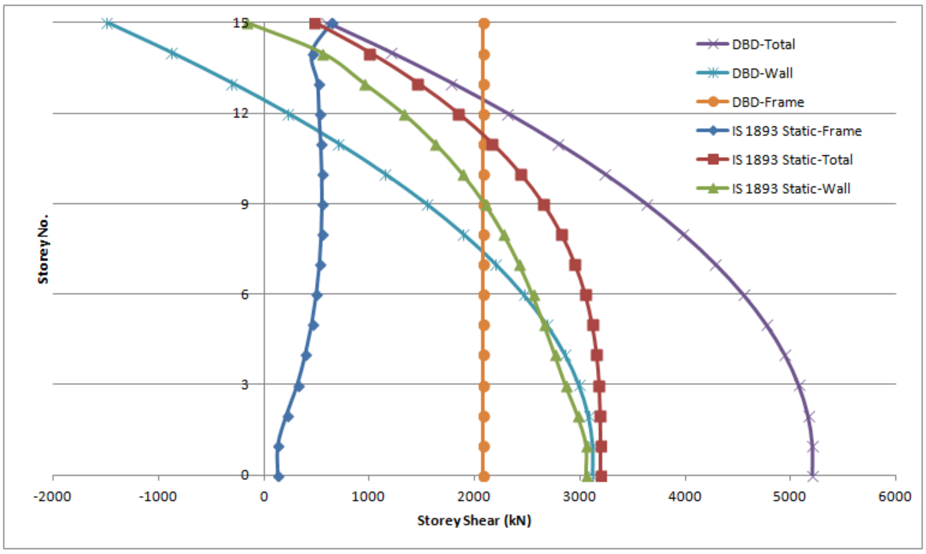

Figure 5.39: Storey Shear Distribution between Frames and Walls by FBD and DBD - Y Direction -$\beta_F = 0.4$

In the below given tables, various parameters time period, ductility, stiffness, etc are compared for DBD and FBD. It can be seen that similar to SDOF system, here also, the time period of FBD is very less than DBD. Also, the actual ductility capacity as per DBD comes out to be very less as compared to the assumed value of 5 as per codal provisions. The system damping comes out to be around 10%. The DBD base shear values are higher as compared to the FBD results.

While increasing the proportion of base shear to be carried by the frame from 0.2 to 0.4 of the total base shear, it is apparent that stiffness, height of contraflexure and base shear values are reducing, while time period, equivalent ductility, damping and ultimate displacements are increasing.

Table 5.4 and 5.5 gives the comparison of various quantities between FBD and DBD with different β_F (=Frame/ Total Base Shear) factors for X and y direction respectively while table 5.6 gives the comparison of various quantities within DBD with different β_F (=Frame/ Total Base Shear) factors.

Table 5.4: Comparison between FBD and DBD for X-direction with different β_F (=Frame/ Total Base Shear)

Response Quantities	FBD @X (Static)	FBD @ X (Dynamic)	DBD @ X ($\beta_F = 0.2$)	DBD @ X ($\beta_F = 0.3$)	DBD @ X ($\beta_F = 0.4$)
Time Period, Te (sec)	0.8	1.3	3.1	3.5	3.9
Ductility	5	5	1.22	1.44	1.67
Base Shear, VB (kN)	3766	3762	6268	5574	5186
Damping (%)	5	5	7.8	9.9	11.6

Table 5.5: Comparison between FBD and DBD for Y-direction with different β_F (=Frame/ Total Base Shear)

Response Quantities	FBD @ Y (Static)	FBD @ Y (Dynamic)	DBD @ Y ($\beta_F = 0.2$)	DBD @ Y ($\beta_F = 0.3$)	DBD @ Y ($\beta_F = 0.4$)
Time Period, Te (sec)	1	1.3	3.4	3.71	4
Ductility	5	5	1.44	1.58	1.72
Base Shear, VB (kN)	3194	3188	5831	5450	5208
Damping (%)	5	5	9.4	10.4	11.1

Table 5.6: Comparison within DBD with different β_F (=Frame/ Total Base Shear)

Response Quantities	**DBD @ X ($\beta_F = 0.2$)**	**DBD @ X ($\beta_F = 0.3$)**	**DBD @ X ($\beta_F = 0.4$)**	**DBD @ Y ($\beta_F = 0.2$)**	**DBD @ Y ($\beta_F = 0.3$)**	**DBD @ Y ($\beta_F = 0.4$)**
Base Shear, V_B (kN)	6268	5574	5186	5831	5450	5208
Stiffness (N/m)	14938529	12231912	10615578	13121284	13778401	10400928
Effective Height (m)	33.3	32.6	32.1	32.7	32.7	31.8
Height of Contraflexure (m)	37.8	32.1	25.8	37.8	38.1	25.8
Ulimate SDOF Displacements (m)	0.420	0.456	0.489	0.444	0.434	0.500
Effective Mass (kg)	3712247	3896056	4061757	3887791	3868248	4134095

5.4.4 Effect of Codal Drift Limit on Ductility of Building

The actual ductility capacity of the building is found to be quite high but because of the smaller codal drift limit imposed on the building, the ductility demand is quite low. **The comparison of various quantities is carried out for $\beta_F = 0.178$ and 0.143 for X and Y- directions respectively** and tabulated in Table 5.7 and the effect of drift limit is noted.

The ductility capacity of the building comes out to be around 3.5 for both the directions, which is in proximity of the codal value of 5. But because of the codal drift limit limit is enforced, the ductility demand reduces to around 1.2. This happens because the yield drift is quite near to the codal drift limit, hence the allowable plastic drift is quite low, which results in low ductility demand.

Table 5.7: Comparison of DBD with and without Drift limit consideration for 15 Storey building

Response Quantities	DBD @ X	DBD @ X - No Code Drift	DBD @ Y	DBD @ Y - No Code Drift
Eff. Mass, me (kg)	3678242	4182900	3811533	4189046
Eff. Stiffness, ke(kN/m)	15492	1811	14372	2285
Design Disp. (mm)	413	1130	426	1013
Total System Damping (%)	7.34	15.9	8.71	15.53
Base Shear, Vb (kN)	6404	2049	6122	2315
Ductility	1.18	3.5	1.35	3.42

5.4.5 Reinforcement Comparison

The ratio of base shear carried by the frames to the total base shear for DBD is kept the same as it is obtained in FBD for comparing the amount of reinforcement required for the columns.

The β_F (=Frame/ Total Base Shear) factor for X and Y directions as per elastic analysis by ETABS comes out to be 0.178 and 0.143 respectively. **Hence, the β_F factor for DBD are kept 0.178 and 0.143 for X and Y directions respectively.**

The comparison of reinforcement for selected columns is carried out and has been tabulated in the table 5.8 below.

The reinforcement demand for the building comes out to be higher in case of DBD as compared to FBD by around 50% some stories. But DBD ensures more safety as it is more realistic as it includes more structural parameters like ductility, hysteresis damping, wall-frame interaction, etc. Owing to inclusion of these factors, DBD is more specific for a given problem rather than the generalized approach given in IS 1893(Part 1)-2002.

Table 5.8: Reinforcement comparison for Columns between FBD and DBD

Story	Column ID	As - Min (sq. mm)	As - FBD (sq. mm)	As- DBD (sq. mm)	% Increase
STORY15	C9	2880	2880	3060	6
STORY10	C9	2880	2880	2880	-
STORY9	C9	2880	2880	2880	-
STORY8	C9	2880	2880	3954	37
STORY7	C9	2880	3449	5223	51
STORY6	C9	2880	5532	6315	14
STORY1	C9	2880	15517	15517	-
STORY15	C10	2880	2880	3029	5
STORY10	C10	2880	2880	2880	-
STORY9	C10	2880	2880	2880	-
STORY8	C10	2880	2880	3394	18
STORY7	C10	2880	4084	4517	11
STORY6	C10	2880	6004	6004	-
STORY1	C10	2880	15746	15746	-

5.5 Summary

A 15 storey RC Wall-Frame building is analysed using ETABS for FBD and DBD is performed using self-prepared Excel sheets and designed. It is found that Time period, Damping and Base shear of the building calculated using DBD increases as compared to FBD. The value of ductility factor achieved through DBD is quite low as compared to assumed ductility factor of FBD. This is evident since inelastic behaviour of building is incorporated in DBD.

Chapter 6

Development of Inelastic Spectra

6.1 Introduction

In this chapter, an attempt has been made to develop the inelastic spectra for Indian context. For the application of this, 4 storey RC frame building is chosen. FBD and DBD is carried out for the same building and the comparison is made.

6.2 Need of Inelastic Spectra

Elastic spectra is the one having a constant value of ductility factor (μ) and response reduction factor (R) for the system, that is they are independent of the time period (T_n). Whereas Inelastic Spectra or Constant-Ductility spectra is the one having a definite R- μ - T_n relationship, so that a constant ductility is obtained for all time periods.

It is advocated in literature that the use of elastic spectra is shown to underestimate significantly the displacement and ductility demands. The problem with elastic spectra is that the ductility factor at low time periods is over-estimated. That is, at low time periods, for stiff structures, R is not equal to μ, instead it is less than μ.

6.3 Construction of Inelastic Spectra

We know that,

$A_y = \omega^2\ D_y$

$A_y = A_u$ / R

$D_y = D_u\ /\ \mu$

where A_u and A_y are the ultimate and yield acceleration and D_u and D_y are the ultimate and yield displacement respectively.

Hence, A_u / R $= \omega^2\ D_u\ /\ \mu$

$$Therefore, D_u = (\mu/R) \times (T_n/2\pi)^2 \times A_u \tag{6.1}$$

in the case of Elastic Spectrum, it is taken that μ is equal to R, hence the above equation reduces to

$$Therefore, D_u = (T_n/2\pi)^2 \times A_u \tag{6.2}$$

While in the case of Inelastic Spectrum, this assumption is not made. Instead a definite relationship is established involving μ and R which varies with Time Period, Tn.

One such well-known R- μ -Tn relationship for the construction of Inelastic Spectra, used in the current work,is given by A. K. Chopra and R. K. Goel based on Newmark and Hall procedure, which is defined as under:

$$R_y = \begin{cases} 1 & T_n < T_a \\ (2\mu - 1)^{\beta/2} & T_a < T_n < T_b \\ \sqrt{2\mu - 1} & T_b < T_n < T_{c'} \\ \dfrac{T_n}{T_c}\mu & T_{c'} < T_n < T_c \\ \mu & T_n > T_c \end{cases}$$

Inelastic spectrum is obtained by the dividing the code-based spectrum by this R- factor instead of the constant R-factor given by the code.

Other R- μ -Tn relationships are also available in literature such as (a) Krawinkler and Nassar, (b) Vidic, Fajfar, and Fischinger, etc. For the comparison purpose, the relation by A. K. Chopra and R. K. Goel [6] is used here.

For the present problem of RC Frame building with Ductile detailing, the R-factor given by the code is 5, which is also the ductility factor μ. Hence, for the ductility μ = 5, Inelastic Spectra needs to be generated.

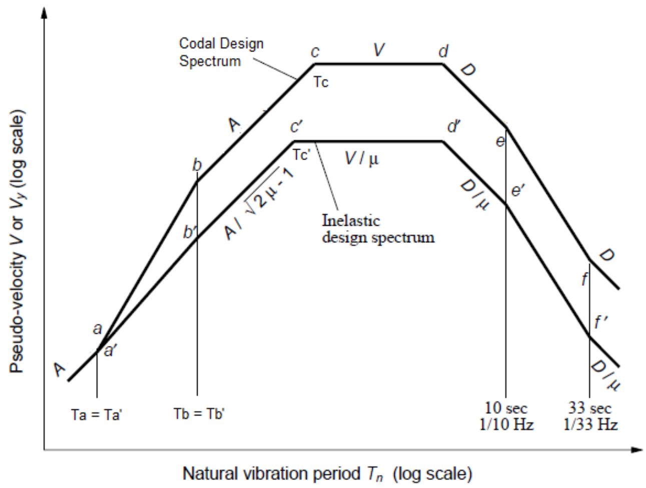

Figure 6.1: Construction of Inelastic Design Spectrum by Newmark-Hall Procedure

For this purpose, it is important to first of all decide the time period intervals viz. T_a, T_b, $T_{c'}$ and T_c as shown in Figure 6.1. In the work by A.K.Chopra[6], T_a is given to be 0.03 sec, hence it is adopted here, as no building will practically be so stiff to have such a low time period. T_b and T_c are the time periods at the two ends of the constant acceleration region of the spectrum. For medium soils, for IS 1893 spectrum, T_b and T_c are 0.10 and 0.55 sec respectively.

$T_{c'}$ is calculated using the R - μ - Tn relationship given above, as shown below,

$$At\ T_n = T_{c'}, R = \sqrt{(}2\mu - 1) \tag{6.3}$$

Also, At the same time period,

$$T_n = T_{c'}, R = (T_n/T_c) \times \mu = (T_{c'}/T_c) \times \mu \tag{6.4}$$

$$Hence, T_{c'} = (T_c/\mu) \times \sqrt{(}2\mu - 1) \tag{6.5}$$

The elastic spectrum is obtained directly by dividing the given IS 1893 spectrum by R value(Response reduction factor). While Inelastic spectrum is obtained by dividing the IS 1893 by the R-value that depends on time. It can be seen that at very low period, there is no force reduction, i.e. R=1 and it then increases to the value of μ = R at the time period T_c, then it remains constant after the time T_c. Hence, after time period T_c, there is no difference between Elastic and Inelastic spectrums.

The relation is shown graphically in the below given Figure 6.2.

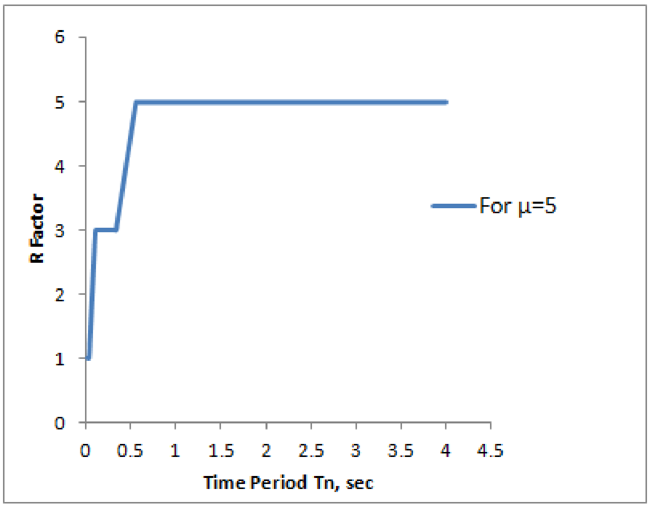

Figure 6.2: Variation of R with Time period (for $\mu = 5$)

The resulting acceleration spectrum showing the elastic as well as inelastic acceleration values is shown in the given Figure 6.3. Figure 6.4 shows the log velocity v/s

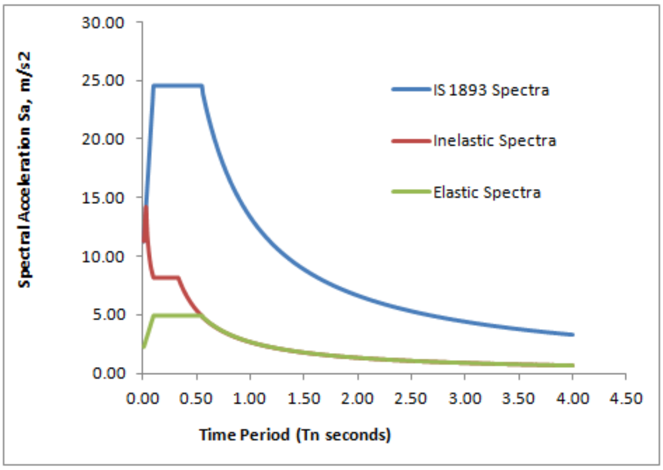

Figure 6.3: Acceleration spectrum - IS 1893, Elastic and Inelastic

log time period graph for the Elastic as well as Inelastic case.

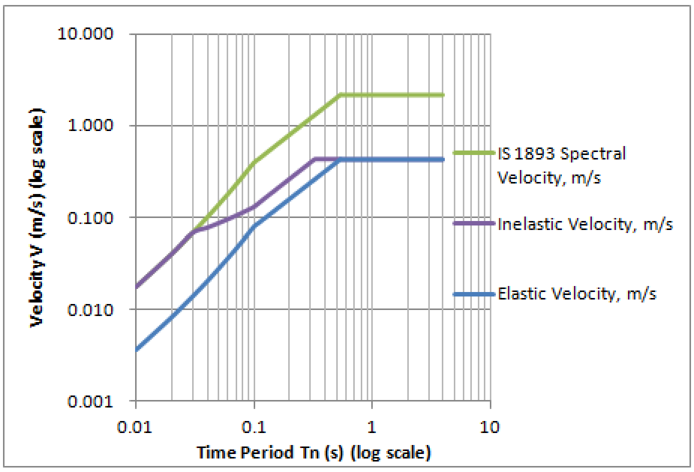

Figure 6.4: Log Velocity v/s Log Time Period - IS 1893, Elastic and Inelastic

6.4 Problem Definition - 4 Storey RC Frame Building

The building shown in Figure 6.5 is 4 storeys high. Following parameters defines the building configuration:

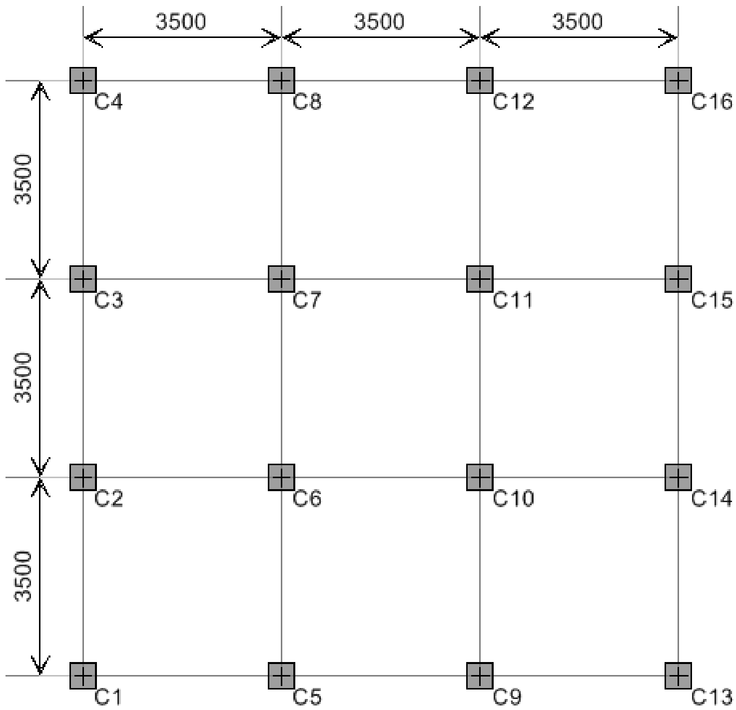

Figure 6.5: Building Plan

No. Of storeys: 4

Storey height: 3m

Building height: 12m

Plan Dimensions: 10.5m x 10.5m

No. Of bays in X-Direction: 3

No. Of bays in Y-Direction: 3

Concrete Grade: M25

Steel Grade: Fe415

Size of Beams: 230mm x 250mm

Size of Columns: 450mm x 450mm

Infill wall thickness = 230 mm on periphery

= 115 mm on internal beams

Parapet height = 1m

Density of concrete = 25 kN/m^3

Density of masonary = 20 kN/m^3

Earthquake Zone: Zone-V (Z=0.36)

Soil type: Medium

Live Load = 3 kN/m^2 on all floors (including roof)

Live Load to considered for Seismic Analysis = 25% on Floors

= 0% on Roof

Importance Factor = 1

Response reduction factor, R = 5 for FBD

6.4.1 Load Calculation

The gravity as well as seismic weight calculations are as follows:

Floor Finish = 1 x 10.5 x 10.5 x 4 = 441 kN

Beams Weight = 4 x 24 x 3.5 x 0.23x 0.25x 25 = 483 kN

Infill Walls : Typical floors : Periphery = 3 x 0.23 x 3 x 10.5 x 4 x 20 = 1739 kN

: Interior walls = 3 x 0.115 x 3 x 10.5 x 4 x 20 = 869 kN

Parapet Walls = 0.23 x 1 x 10.5 x 4 x 20 = 193 kN

Columns weight = 12 x 16 x 0.45 x 0.45 x 25 = 972 kN

Slab Weight = 0.120 x 25 x 10.5 x 10.5 x 4 = 1323 kN

Total Dead Load (DL) = 6020 kN

Total Live Load for Floors, except Roof = 3 x 10.5 x 10.5 x 3 = 992 kN

Total Live Load for Roof = 3 x 10.5 x 10.5 = 331 kN

Total Seismic Weight of the Building, We = 6020 + 0.25 x 992 + 0 x 331 - 972/(2x 4) = 6147 kN

Seismic Wt of typical storey,

Wi = (441+483+1323+972/2)/4 + (1739+869)/3 + 0.25 x 992/4 = 1615 kN = 164585 kg

Seismic Wt of typical roof,

Wr = (441+483+1323+972/2)/4 + 193 + 0 x 331 = 876 kN = 89322 kg

6.5 Force Based Design

FBD usig Elastic as well as Inelastic Spectra has been carried out in this section. The empirical time period as per IS 1893 (Part 1/0: 2002 is given by

T_n = 0.075 x $h^{0.75}$

where h = height of the building

Hence, the time period comes out to be

T_{nx} = T_{nx} = 0.075 x $12^{0.75}$ = 0.483 sec

At time T = 0.483 sec, from the Inelastic Spectrum generated above, R = 4.39.

For the conventional case using elastic spectrum, R = 5

The Static Base shear is given by,

V_B = Z/2 x I/R x Sa/g x We

The EQ analysis is carried out using ETABS.

Table 6.1: Storey Shears

Storey	IS 1893 Elastic	IS 1893 Inelastic
4	198	226
3	423	482
2	523	596
1	548	624
Base	548	624

6.6 Displacement Based Design

The Displacement based design for both the direction will be identical because of the symmetrical geometry of the building. It is explained step by step in this section.

STEP I. **Material Constants**

First of all, important parameters required for the design are calculated:

The reinforcement grade is Fe 415. Hence, fy= 415 MPa.

The expected yield strength of the reinforcing bar is

fye=0.87fy = 0.87 x 415 = 361.05 MPa

The yield strain of the reinforcement is given by:

ε_y = fye/E

where E = Modulus of Elasticity of Steel = 2x 10^5 MPa

Hence, ε_y = 361.05/(2x10^5) = 0.0018

The yield drift for the building will be governed by the yielding of the beams because of the strong column-weak beam concept and is given by:

θ_{yF} = 0.5 x ε_Y x Lb / h_b

= 0.5 x 0.0018 x 3.5 x 0.25

= 0.0126 rad

The code based drift limit as per IS 1893(Part 1) :2002 is θ_c = 0.004 x 5 (Ductility factor for Ductile RC Frame buildings) = 0.02.

STEP II. **Displacement Profile Calculations**

Upto four storey building, the displacement follows a linear mode shape.

$$Hence,\ \delta = H_i/H_n \tag{6.6}$$

Table 6.2: Displacement Profile Calculations

Floor i	Hi (m)	mi (kg)	Δ_{di} (m)	mi x Δ_{di}	mi x Δ_{di}^2	mi x Δ_{di} x Hi
4	12	89322	0.240	21437	5145	257247
3	9	164585	0.180	29625	5333	266628
2	6	164585	0.120	19750	2370	118501
1	3	164585	0.060	9875	593	29625
0	0	0	0.000	0	0	0
Sum		583077		80688	13440	672002

For no. of storeys, n > 4,

$$\delta = 4/3 \times H_i/H_n \times (1 - H_i/4H_n) \tag{6.7}$$

In the above equations, H_i and H_n are the heights of level i and the roof (level n) respectively. Displacement shapes resulting from the above equations provide agreement with those resulting from inelastic time-history analysis for taller buildings.

Calculations necessary to determine the displacement profile and hence, the effective height and the design displacement for wall is summarized in below given table 6.2.

STEP III. **Effective Height**

From Table 4.3, the effective height is given by:

$$He = \frac{\sum_{i=1}^{n} m_i \times \Delta_i \times Hi}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{6.8}$$

Therefore, He = 672002/80688 = 8.33 m

STEP IV. **Design SDOF Displacement**

From table 4.3, the design displacement of the SDOF substitute structure is given by:

$$\Delta_D = \frac{\sum_{i=1}^{n} m_i \times \Delta_i^2}{\sum_{i=1}^{n} m_i \times \Delta_i} \tag{6.9}$$

Δ_D = 13440/80688 = 0.167 m

STEP V. **Yield SDOF Displacement**

The yield displacement the SDOF substitute structure is calculated substituting He in above equation,

$\Delta_y = \theta_y$ x H_e

= 0.0126 x 8.33

= 0.105 m

STEP VI. **Equivalent Damping**

The ductility of frames is:

$$\mu = \Delta_D/\Delta_{YW} \tag{6.10}$$

μ = 0.167 / 0.105 = 1.58

The effective damping is given by:

ξ_{sys} = 0.05 + 0.565 (μ -1)/ (μ x π) = 0.1162 = 11.62 %

Hence, the modification factor(m.f.) for damping as per table 3 of IS 1893 (Part 1):2002,

m.f. = 0.77

STEP VII. **Effective mass**

The Effective Mass of the SDOF system is given by

$$m_e = \frac{\sum_{i=1}^{n} m_i \times \Delta_i}{\Delta_d} \tag{6.11}$$

Hence, me = 80688/0.167

= 484414 kg

STEP VIII. **Base Shear**

The Base Shear of the SDOF system as per the formula derived in section 4.2, is given by

V_B = 2.255 x Z x m_e x m.f. x I / Δ_d

= 2.255 x 0.36 x 484414 x 0.77 x 1 / 0.167

= 1812 kN

STEP IX. **Effective Stiffness**

The Effective Stiffness of the SDOF system is given by

Ke = V_B / Δ_D = 1812 / 0.167 = 10879 kN/m

STEP X. **Effective Time Period**

The Effective Time Period of the SDOF system is given by

Te = 2π x $\sqrt{}$(me/ke)

= 2 x 3.14 x $\sqrt{}$(484414 / 10879000)

= 1.33 seconds

As the time period is 1.33 seconds, being greater than 0.55 seconds, the elastic and inelastic spectra gives same response reduction factor. Hence, DBD, for this case, unlike FBD, will give same base shear for both the cases, viz. Elastic as well as Inelastic

6.7 Results and Discussions

Figure 6.6 and Figure 6.7 shows the comparison of Displacement across the height of the building by FBD- Elastic and Inelastic and DBD. The displacement by Inelastic spectra comes out to be 10% higher. The displacement by DBD shown here is the design displacement which comes out to be around 8 to 10 times that by FBD- Elastic.

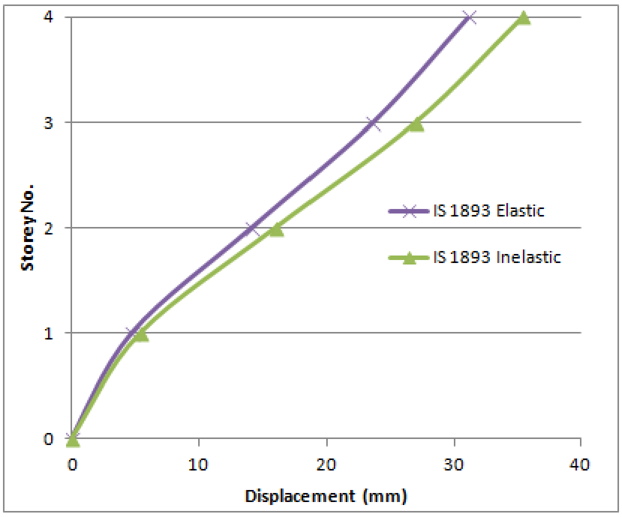

Figure 6.6: Displacement Comparison between FBD - Elastic and Inelastic spectra

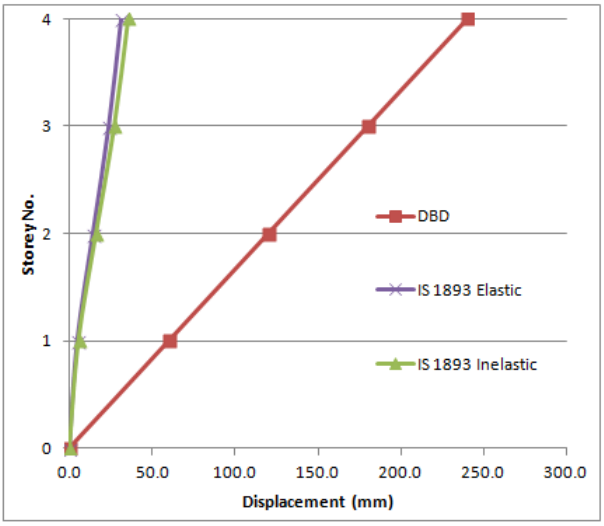

Figure 6.7: Displacement Comparison among FBD and DBD

Figure 6.8 shows the drift comparison of the FBD-Elastic and Inelasic Spectrum case. DBD case is not shown here as the drift of 0.02 is constant throughout the height of the building.

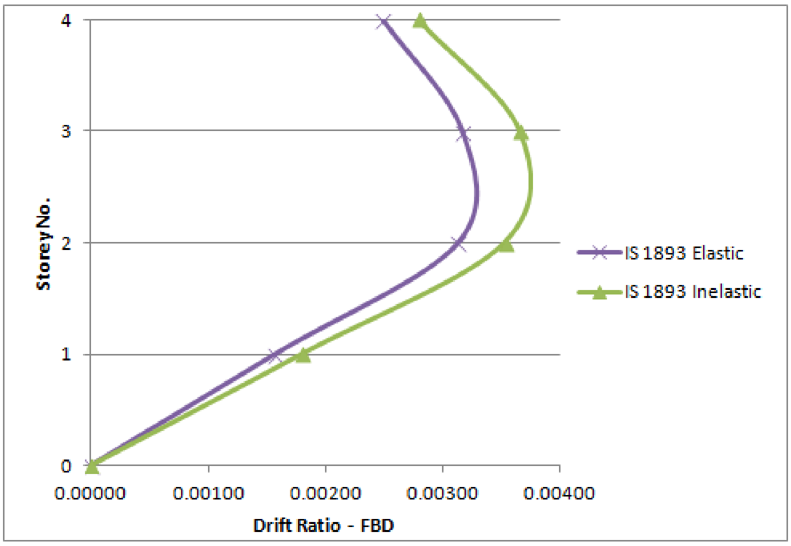

Figure 6.8: Drift Comparison

Figure 6.9 shows the storey shear profile for the three cases. As compared to FBD-Elastic, FBD-inelastic gives 10% higher storey shear, and DBD gives 3 times higher storey shear.

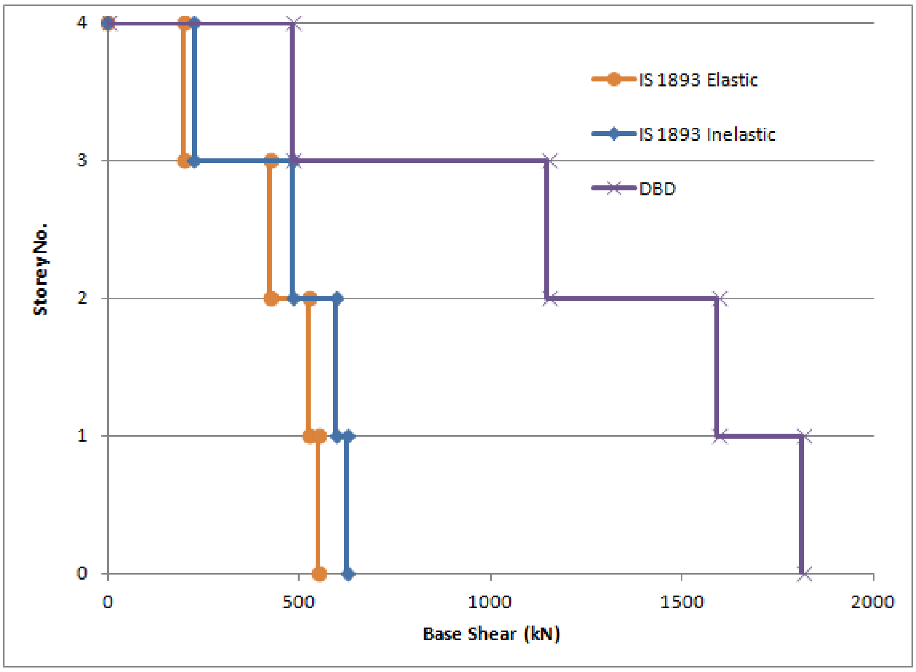

Figure 6.9: Storey Shear

Figure 6.10 shows the variation of the lateral forces across the height of the building for the three cases. Inelastic gives 10% more lateral forces, whereas for DBD, it increases by 2 times at the top storey to 9 times in the first storey.

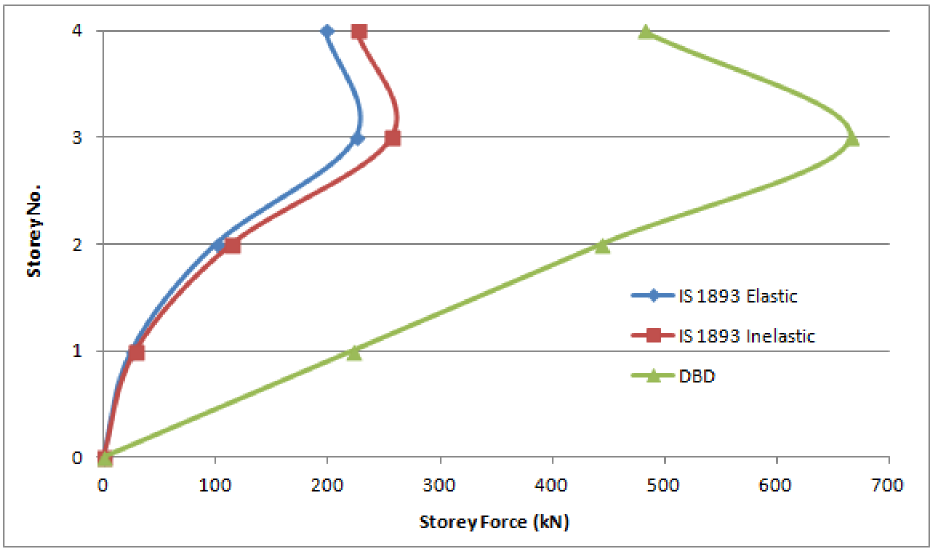

Figure 6.10: Lateral Forces

Figure 6.11 shows the moment distribution across the height of the building as per FBD- (Elastic and Inelastic) and DBD.

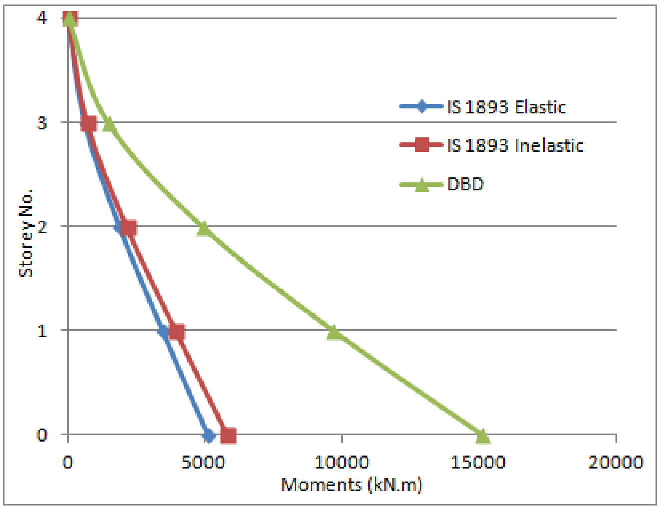

Figure 6.11: Overturning Moment Comparison

Table 6.3 shows that the time period is higher in DBD and ductility is lower. Also, the damping is higher and the base shear comes out to be higher. Also, in **Inelastic Spectrum** case, the base shear is 14% higher than the elastic case.

The time period of FBD comes out to be very less than DBD. Also, the actual ductility factor as per DBD comes out to be very less as compared to the assumed value of 5 as per codal provisions. The system damping comes out to be around 12%. The DBD base shear values are higher as compared to the FBD results.

Table 6.4 gives the reinforcement requirements of columns for all the three cases.

Table 6.3: Comparison of FBD and DBD

Response Quantities	FBD Elastic	FBD Inelastic	DBD
Time Period, Te (sec)	0.483	0.483	1.33
Ductility	5.00	5.00	1.58
Base Shear, V_B (kN)	548	624	1812
Damping (%)	5.0	5.0	11.62

Table 6.4: Percentage Reinfo. in columns

Story	Pt (%) - FBD Elastic	Pt (%) - FBD Inelastic	Pt (%) - DBD
STORY4	0.80	0.80	0.80
STORY3	0.80	0.80	0.80
STORY2	0.80	0.80	1.83
STORY1	1.39	1.49	4.92
STORY4	0.80	0.80	0.80
STORY3	0.80	0.80	0.87
STORY2	0.80	0.81	2.53
STORY1	1.29	1.42	5.17
STORY4	0.80	0.80	0.80
STORY3	0.80	0.80	0.87
STORY2	0.80	0.81	2.53
STORY1	1.29	1.42	5.17
STORY4	0.80	0.80	0.80
STORY3	0.80	0.80	0.85
STORY2	0.80	0.80	2.49
STORY1	1.22	1.37	5.16

Table 6.5 shows the comparison of the reinforcements of Four columns C1, C2, C5, C6 for all three cases viz. FBD-Elastic, Inelastic and DBD. When using Inelastic spectrum for FBD, the reinforcement requirement for the ground floor comes out to be around 10% more than the FBD with elastic spectrum. While for DBD, the reinforcement requirements for the bottom two storeys comes out to be 2 to 3 times.

Table 6.5: Column Reinforcement Comparison

Storey	**Column ID**	**As - FBD Elastic**	**As - FBD Inelastic**	**As - DBD**	**% increase in Reinfo.**	**% increase in Reinfo.**
		mm^2	mm^2	mm^2	**- FBD Inelastic**	**- DBD**
STORY4	C1	1620	1620	1620	-	-
STORY3	C1	1620	1620	1620	-	-
STORY2	C1	1620	1620	3701	-	128
STORY1	C1	2814	3025	9958	7	254
						-
STORY4	C2	1620	1620	1620	-	-
STORY3	C2	1620	1620	1755	-	8
STORY2	C2	1620	1646	5132	2	217
STORY1	C2	2611	2868	10469	10	301
STORY4	C5	1620	1620	1620	-	-
STORY3	C5	1620	1620	1755	-	8
STORY2	C5	1620	1646	5132	2	217
STORY1	C5	2611	2868	10469	10	301
STORY4	C6	1620	1620	1620	-	-
STORY3	C6	1620	1620	1730	-	7
STORY2	C6	1620	1620	5045	-	211
STORY1	C6	2477	2768	10450	12	322

6.8 Summary

Inelastic spectra is prepared for medium soil sites for the ductility factor of 5. For the comparison, it is applied to an RC Frame building. Then it is compared with the elastic spectra. The base shear by Inelastic spectra comes out to be 14% higher. Then DBD is also applied to the building then compared with the above two cases.

Chapter 7

Summary and Conclusions

7.1 Summary

The main objective of the work carried out is to study the displacement based design procedure for the shear wall buildings and wall-frame buildings. The present seismic design method available in codes i.e. FBD is, first of all, critically reviewed and drawbacks are discussed. The DBD procedure is illustrated using a simple SDOF system. For MDOF system, the procedure, called Substitute Structure method, to convert an MDOF system to an equivalent SDOF system is explained.

DBD is applied to two Shear wall buildings of 15 and 25 storeys having the same plan and results are compared with FBD. Actual ductility capacity and ductility demand of the building and their effect on quantities like base shear, stiffness, etc is studied.

Application of DBD to wall-frame system is illustrated with the help of a 15 storey building problem. Iterations are carried out using different frame shear proportions. Results are then compared between DBD and FBD. Attempt is made to calculate actual ductility of the building and the effect of codal drift limit. Also, Column reinforcement is compared between FBD and DBD.

Also, an attempt is made to develop an Inelastic Spectra for the Indian context using the Code based spectra as input, for time period upto 4 seconds. An RC Frame building of 4 storeys is taken as example. The difference in results with the use of elastic and inelastic spectra are presented. Also DBD is performed on the building and compared with FBD.

7.2 Conclusions

Based on the current study, following set of conclusion are made:

- It is concluded that DBD provides higher base shear values than FBD, which may be actual case.
- For DBD, for 15 storey building, Shear wall building gives higher base shear than Wall-frame building.
- The time period is lesser in Shear Wall buildings, being comparatively stiffer.
- The ductility demand of wall-frame comes out to be 1.2 whereas for shear wall it is 1.
- Due to the codal restrictions on drift limits, the required ductility demand of the building comes out to be low.
- But the building is capable of providing higher displacements, hence its available ductility capacity is much higher than the demand.
- It comes out to be around 3.5 for wall-frame building and around 3.2 for shear wall building.
- One of the factors for higher base shear and lower ductility demand of shear wall buildings is that the response reduction factor (=ductility factor) and hence the maximum allowable ultimate drift as per the code is lower for shear wall buildings as compared to wall-frame buildings.

- As expected, the design displacement of wall-frame building comes out to be higher than the shear wall buildings.
- The Inelastic spectra is generated and applied to a 4 storey RC frame building.
- As a result, there is a considerable increase in various response quantities as compared to Elastic spectra.
- It is advocated that for low period structures, Inelastic spectra should be used to get the desired amount of ductility.

7.3 Future Scope of Work

The future scope of work includes:

I. Displacement based design of Steel structures like steel frame building, etc.

II. Comparison of Displacement based design of Shear wall and Wall-frame building using non-linear time-history analysis.

III. Extent DBD for other structures like bridge structures, water tanks, etc.

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Appendix A

Force Based Design of Shear Wall Buildings

Empirical Fundamental Time period as per IS 1893:

T = 0.09h/ $\sqrt{d}$

where h = Height of the building;

d = Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force

Time Period in X-Direction, Tx = 0.09 x 45/ $\sqrt{25}$ = 0.81 seconds

Time Period in Y-Direction, Ty = 0.09 x 45/ $\sqrt{18}$ = 0.955 seconds

Therefore, as per IS 1893:2002 cl. 6.4.5,

(Sa/g)x = 1.36/Tx = 1.36/ 0.81

(Sa/g)x = 1.36/Tx = 1.36/ 0.955

Ah(x) = 0.36/2 x 1/5 x 1.36/0.810 = 0.06040

Ah(y) = 0.36/2 x 1/5 x 1.36/0.955 = 0.05123

The Static Base shear is given by,

V_B = Z/2 x I/R x Sa/g

For Code Based EQ analysis, ETABS is used and the user defined time period as given above is used. A separate live load case for Roof is created which is not

Table A.1: IS code - Static and Dynamic Base Shear

Storeys	**Static-X**	**Dynamic-X**	**Static-Y**	**Dynamic-Y**
15	573	601	486	519
14	1213	1183	1029	1025
13	1765	1614	1497	1393
12	2235	1943	1896	1660
11	2630	2215	2231	1870
10	2957	2453	2508	2055
9	3221	2669	2732	2234
8	3430	2875	2910	2408
7	3590	3078	3045	2579
6	3708	3275	3145	2749
5	3790	3461	3214	2917
4	3842	3630	3259	3073
3	3871	3770	3283	3197
2	3884	3861	3295	3273
1	3888	3895	3297	3301
Base	3888	3895	3297	3301

included in Mass Source function. A factor 0.25 for Live load on Floors and 1 for Dead Load (including Floor Finish) is used in the same.

Therefore, Base Shear in X and Y-Direction are given by,

By Static Analysis, EQX = 3900 kN

And EQY = 3330 kN

By Dynamic Analysis as per IS 1893,

SpecX = 2167 kN

SpecY = 2197 kN

Hence, as per Cl 7.8.2 IS 1893 : 2002, this base shear values needs to be multiplied by VB (static)/ VB (Dynamic).

[VB (static)/ VB (Dynamic)]X = 1.8

[VB (static)/ VB (Dynamic)]Y = 1.516

The storey shear values have been given in the below table, for both X and Y - direction.

Appendix B

Force Based Design of Wall-Frame Buildings

Empirical Fundamental Time period as per IS 1893:

$T = 0.09h/\sqrt{d}$

where h = Height of the building;

d = Base dimension of the building at the plinth level, in m, along the considered direction of the lateral force

Time Period in X-Direction, $Tx = 0.09 \times 45/\sqrt{25} = 0.81$ seconds

Time Period in Y-Direction, $Ty = 0.09 \times 45/\sqrt{18} = 0.955$ seconds

Therefore, as per IS 1893:2002 cl. 6.4.5,

$(Sa/g)x = 1.36/Tx = 1.36/0.81$

$(Sa/g)x = 1.36/Tx = 1.36/0.955$

$Ah(x) = 0.36/2 \times 1/5 \times 1.36/0.810 = 0.06040$

$Ah(y) = 0.36/2 \times 1/5 \times 1.36/0.955 = 0.05123$

The Static Base shear is given by,

$V_B = Z/2 \times I/R \times Sa/g$

For Code Based EQ analysis, ETABS is used and the user defined time period as given above is used. A separate live load case for Roof is created which is not

Table B.1: IS code - Static and Dynamic Base Shear

Storeys	**Static-X**	**Dynamic-X**	**Static-X**	**Dynamic-Y**
15	565	605	479	523
14	1183	1171	1004	1017
13	1716	1580	1456	1367
12	2170	1888	1841	1612
11	2552	2140	2164	1797
10	2867	2357	2432	1961
9	3123	2552	2648	2121
8	3324	2742	2819	2282
7	3479	2934	2951	2445
6	3592	3126	3047	2612
5	3671	3311	3114	2783
4	3722	3483	3157	2945
3	3750	3628	3181	3076
2	3763	3725	3191	3158
1	3766	3762	3194	3188
0	3766	3762	3194	3188

included in Mass Source function. A factor 0.25 for Live load on Floors and 1 for Dead Load (including Floor Finish) is used in the same.

Therefore, Base Shear in X and Y-Direction are given by,

By Static Analysis, EQX = 3766 kN

And EQY = 3194 kN

By Dynamic Analysis as per IS 1893,

SpecX = 1946 kN

SpecY = 1944 kN

Hence, as per Cl 7.8.2 IS 1893 : 2002, this base shear values needs to be multiplied by VB (static)/ VB (Dynamic).

[VB (static)/ VB (Dynamic)]X = 1.933

[VB (static)/ VB (Dynamic)]Y = 1.64

The storey shear values have been given in the below table, for both X and Y - direction.

The β_F factor i.e the base shear proportion carried by frame of the total base shear is found to be 0.178 and 0.143 for X and Y directions respectively by FBD method of analysis using ETABS

Appendix C

Excel sheets - Shear wall buildings

C.1 15 Storey Building

C.1.1 X - Direction

Table C.1: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Height of Building, H_n =	45	m
Zone Factor, Z=	0.36	
Assumed Effective Height , H_e=	33.75	m
Beam Length, L_b=	5	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	5	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000913	per m

Design Displacement Profile:		
Wall Material strains:		
Damage control curvature, f_{dc}=	0.0144	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	MPa
k	0.0337	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.84	m
Check if the code based drift limit is exceeded:		
θ_y=	0.0206	rad
θ_p=	0.0248	rad
θ_{cf}=	0.0454	rad
Code Based drift limit, θ_c	0.016	rad
Hence, Governing drift, θ_c=	0.016	rad
Governing θ_y=	0.016	rad
Governing θ_p=	0.000	rad
Drift limits:		
Drift Amplification Factor, ω_o=	0.975	
Reduced Design Drift, θ_r=	0.0156	rad
Reduced θ_y=	0.0156	rad
Reduced θ_p=	0.0000	rad
Δ_{yi}=	0.4701	m
Roof Level Design Displacement, Δ_d=	0.470	m

Design SDOF Displacement:		
Δ_d=	0.303	m
Effective Height:		
H_e=	33.63	m

Equivalent Damping:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.303	m
Wall Displ. Ductility, μ_w=	1.00	
Wall Damping, ξ_w=	5.0000	%

Base Shear Force:		
Eff. Time Period, T_e=	2.12	sec
Eff. Mass, m_e=	4047822	kg
Eff. Stiffness, K_e=	35718	kN/m
Base Shear, V_b=	10834	kN

Table C.2: DBD Displacement Profile

Floor i	**Hi (m)**	**mi (kg)**	θ_{yi} **(rad)**	Δ_{yi} **(m)**	θ_{pi} **(rad)**	Δ_{pi} **(m)**	Δ_{di} **(m)**	**mi** Δ_{di}	**mi** Δ_{di}^2	**mi** Δ_{di} **Hi**
15	45	346106	0.0156	0.468	0.0000	0.000	0.468	161978	75806	7288992
14	42	443629	0.0156	0.421	0.0000	0.000	0.421	186887	78730	7849265
13	39	443629	0.0156	0.375	0.0000	0.000	0.375	166341	62370	6487289
12	36	443629	0.0156	0.329	0.0000	0.000	0.329	146163	48157	5261879
11	33	443629	0.0156	0.285	0.0000	0.000	0.285	126540	36094	4175805
10	30	443629	0.0156	0.243	0.0000	0.000	0.243	107654	26124	3229619
9	27	443629	0.0156	0.202	0.0000	0.000	0.202	89691	18133	2421660
8	24	443629	0.0156	0.164	0.0000	0.000	0.164	72836	11958	1748054
7	21	443629	0.0156	0.129	0.0000	0.000	0.129	57272	7394	1202710
6	18	443629	0.0156	0.097	0.0000	0.000	0.097	43185	4204	777323
5	15	443629	0.0156	0.069	0.0000	0.000	0.069	30758	2133	461374
4	12	443629	0.0156	0.045	0.0000	0.000	0.045	20177	918	242129
3	9	443629	0.0156	0.026	0.0000	0.000	0.026	11627	305	104640
2	6	443629	0.0156	0.012	0.0000	0.000	0.012	5290	63	31743
1	3	443629	0.0156	0.003	0.0000	0.000	0.003	1353	4	4060
0	0	0	0	0	0	0	0	0	0	0
Sum	0	6556911	0	2.870		0.000	2.870	1227752	372392	41286543

Table C.3: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	46.3	37.8	468.0	468.0
14	43.3	35.4	421.3	421.3
13	40.1	32.9	375.0	375.0
12	36.8	30.3	329.5	329.5
11	33.3	27.5	285.2	285.2
10	29.6	24.6	242.7	242.7
9	25.8	21.6	202.2	202.2
8	22.0	18.5	164.2	164.2
7	18.1	15.4	129.1	129.1
6	14.3	12.3	97.3	97.3
5	10.8	9.3	69.3	69.3
4	7.5	6.5	45.5	45.5
3	4.6	4.1	26.2	26.2
2	2.3	2.0	11.9	11.9
1	0.7	0.6	3.1	3.1
0	0.0	0.0	0.0	0.0

Table C.4: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.0010	0.0008	0.0156	0.0156
14	0.0011	0.0009	0.0154	0.0154
13	0.0011	0.0009	0.0152	0.0152
12	0.0012	0.0010	0.0147	0.0147
11	0.0012	0.0010	0.0142	0.0142
10	0.0013	0.0010	0.0135	0.0135
9	0.0013	0.0010	0.0127	0.0127
8	0.0013	0.0011	0.0117	0.0117
7	0.0013	0.0010	0.0106	0.0106
6	0.0012	0.0010	0.0093	0.0093
5	0.0011	0.0009	0.0080	0.0080
4	0.0010	0.0008	0.0064	0.0064
3	0.0008	0.0007	0.0048	0.0048
2	0.0005	0.0005	0.0030	0.0030
1	0.0002	0.0002	0.0010	0.0010
0	0	0	0	0

Table C.5: Shear Distribution

Level	**Height Hi (m)**	**Mass mi (kg)**	**miHi**	$F_{i(relative)}$	$V_{i(relative)}$	$M_{i(relative)}$	V_i	M_i
15	45	346106	15574770	0.100	0.100	0.000	1086	0
14	42	443629	18632416	0.120	0.220	0.301	2386	3259
13	39	443629	17301529	0.111	0.332	0.962	3593	10417
12	36	443629	15970642	0.103	0.434	1.956	4707	21196
11	33	443629	14639755	0.094	0.529	3.260	5728	35316
10	30	443629	13308869	0.086	0.614	4.846	6656	52500
9	27	443629	11977982	0.077	0.692	6.689	7492	72469
8	24	443629	10647095	0.069	0.760	8.764	8234	94945
7	21	443629	9316208	0.060	0.820	11.044	8884	119648
6	18	443629	7985321	0.051	0.871	13.504	9441	146301
5	15	443629	6654434	0.043	0.914	16.119	9905	174625
4	12	443629	5323547	0.034	0.949	18.861	10277	204342
3	9	443629	3992661	0.026	0.974	21.707	10555	235172
2	6	443629	2661774	0.017	0.991	24.630	10741	266838
1	3	443629	1330887	0.009	1.000	27.604	10834	299061
0	0	0	0	0.000	1.000	30.604	10834	331563
Sum		6556911	155317889	1.000				

Table C.6: Lateral Forces Comparison (in kN)

Storey	**IS 1893 Static**	**IS 1893 Dynamic**	**DBD**
15	573	601	1086
14	640	582	1300
13	552	430	1207
12	470	330	1114
11	395	272	1021
10	327	238	928
9	264	216	835
8	209	206	743
7	160	203	650
6	118	197	557
5	82	186	464
4	52	169	371
3	29	139	278
2	13	91	186
1	3	34	93
0	0	0	0

Table C.7: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	573	601	1086
14	1213	1183	2386
13	1765	1614	3593
12	2235	1943	4707
11	2630	2215	5728
10	2957	2453	6656
9	3221	2669	7492
8	3430	2875	8234
7	3590	3078	8884
6	3708	3275	9441
5	3790	3461	9905
4	3842	3630	10277
3	3871	3770	10555
2	3884	3861	10741
1	3888	3895	10834
0	3888	3895	10834

Table C.8: Moment Distribution (in kN.m)

Storey	IS Static	IS Dynamic	DBD
15	0	0	0
14	1720	1803	3259
13	5360	5352	10417
12	10655	10193	21196
11	17361	16022	35316
10	25252	22668	52500
9	34123	30027	72469
8	43787	38034	94945
7	54078	46660	119648
6	64849	55893	146301
5	75973	65718	174625
4	87342	76102	204342
3	98868	86993	235172
2	110481	98303	266838
1	122134	109885	299061
0	133797	121570	331563

C.1.2 Y - Direction

Table C.9: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Height of Building =	45	m
Zone Factor, Z=	0.36	
Assumed Effective Ht , H_e=	33.75	m
Beam Length, L_b=	6	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	6	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000760833	per m
Design Displacement Profile:		
Wall Material strains:		
Damage control curvature, f_{dc}=	0.012	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	MPa
k	0.0337	
Assume diameter of Longi. Reinfo., d_{b1}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.94	m

Check if the code based drift limit is exceeded:		
θ_y=	0.0172	rad
θ_p=	0.0218	rad
θ_{cf}=	0.0390	rad
Code Based drift limit, θ_c	0.016	rad
Hence, Governing drift, θ_c=	0.016	rad
Governing θ_y=	0.016	rad
Governing θ_p=	0.000	rad
Drift limits:		
Drift Amplification Factor, ω_o=	0.975	
Reduced Design Drift, θ_r=	0.0156	rad
Reduced θ_y=	0.0156	rad
Reduced θ_p=	0.0000	rad
Δ_{yi}=	0.4701	m
Roof Level Design Displacement, Δ_d=	0.470	m
Design SDOF Displacement:		
Δ_d=	0.303	
Effective Height:		
He=	33.63	m
Equivalent Damping:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.303	m
Wall Displ. Ductility, μ_w=	1.00	
Wall Damping, μ_w=	5.0000	%
Base Shear Force:		
Eff. Time Period, T_e=	2.12	sec
Eff. Mass, m_e=	4047822	kg
Eff. Stiffness, K_e=	35718	kN/m
Base Shear, V_b=	10834	kN

Table C.10: DBD Displacement Profile

Floor i	**Hi (m)**	**mi (kg)**	θ_{yi} **(rad)**	Δ_{yi} **(m)**	θ_{pi} **(rad)**	Δ_{pi} **(m)**	Δ_{di} **(m)**	**mi** Δ_{di}	**mi** Δ_{di}^2	**mi** Δ_{di} **Hi**
15	45	346106	0.0156	0.4680	0.0000	0.000	0.468	161978	75806	7288992
14	42	443629	0.0156	0.4213	0.0000	0.000	0.421	186887	78730	7849265
13	39	443629	0.0156	0.3750	0.0000	0.000	0.375	166341	62370	6487289
12	36	443629	0.0156	0.3295	0.0000	0.000	0.329	146163	48157	5261879
11	33	443629	0.0156	0.2852	0.0000	0.000	0.285	126540	36094	4175805
10	30	443629	0.0156	0.2427	0.0000	0.000	0.243	107654	26124	3229619
9	27	443629	0.0156	0.2022	0.0000	0.000	0.202	89691	18133	2421660
8	24	443629	0.0156	0.1642	0.0000	0.000	0.164	72836	11958	1748054
7	21	443629	0.0156	0.1291	0.0000	0.000	0.129	57272	7394	1202710
6	18	443629	0.0156	0.0973	0.0000	0.000	0.097	43185	4204	777323
5	15	443629	0.0156	0.0693	0.0000	0.000	0.069	30758	2133	461374
4	12	443629	0.0156	0.0455	0.0000	0.000	0.045	20177	918	242129
3	9	443629	0.0156	0.0262	0.0000	0.000	0.026	11627	305	104640
2	6	443629	0.0156	0.0119	0.0000	0.000	0.012	5290	63	31743
1	3	443629	0.0156	0.0031	0.0000	0.000	0.003	1353	4	4060
0	0	0	0	0	0	0	0	0	0	0
Sum	0	6556911	0	2.870		0.000	2.870	1227751.798	372391.538	41286543

Table C.11: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	40.3	32.4	468.0	468.0
14	37.2	29.9	421.3	421.3
13	34.0	27.4	375.0	375.0
12	30.7	24.8	329.5	329.5
11	27.4	22.2	285.2	285.2
10	24.1	19.5	242.7	242.7
9	20.7	16.9	202.2	202.2
8	17.3	14.2	164.2	164.2
7	14.1	11.6	129.1	129.1
6	11.0	9.2	97.3	97.3
5	8.1	6.8	69.3	69.3
4	5.6	4.7	45.5	45.5
3	3.4	2.9	26.2	26.2
2	1.6	1.4	11.9	11.9
1	0.5	0.4	3.1	3.1
0	0.0	0.0	0.0	0.0

Table C.12: Drift Comparison

IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
0.00104	0.00082	0.01558	0.01558
0.00106	0.00084	0.01544	0.01544
0.00109	0.00086	0.01516	0.01516
0.00111	0.00087	0.01474	0.01474
0.00112	0.00088	0.01419	0.01419
0.00112	0.00089	0.01350	0.01350
0.00111	0.00088	0.01266	0.01266
0.00108	0.00086	0.01169	0.01169
0.00103	0.00083	0.01058	0.01058
0.00096	0.00078	0.00934	0.00934
0.00086	0.00071	0.00795	0.00795
0.00073	0.00061	0.00642	0.00642
0.00058	0.00049	0.00476	0.00476
0.00038	0.00033	0.00296	0.00296
0.00016	0.00014	0.00102	0.00102
0	0	0	0

Table C.13: Shear Distribution (in kN)

Level	**Height Hi (m)**	**Mass mi (kg)**	$m_i\ H_i$	$F_{i(relative)}$	$V_{i(relative)}$	$M_{i(relative)}$	V_i	M_i
15	45	346106	15574770	0.100	0.100	0.000	1086	0
14	42	443629	18632416	0.120	0.220	0.301	2386	3259
13	39	443629	17301529	0.111	0.332	0.962	3593	10417
12	36	443629	15970642	0.103	0.434	1.956	4707	21196
11	33	443629	14639755	0.094	0.529	3.260	5728	35316
10	30	443629	13308869	0.086	0.614	4.846	6656	52500
9	27	443629	11977982	0.077	0.692	6.689	7492	72469
8	24	443629	10647095	0.069	0.760	8.764	8234	94945
7	21	443629	9316208	0.060	0.820	11.044	8884	119648
6	18	443629	7985321	0.051	0.871	13.504	9441	146301
5	15	443629	6654434	0.043	0.914	16.119	9905	174625
4	12	443629	5323547	0.034	0.949	18.861	10277	204342
3	9	443629	3992661	0.026	0.974	21.707	10555	235172
2	6	443629	2661774	0.017	0.991	24.630	10741	266838
1	3	443629	1330887	0.009	1.000	27.604	10834	299061
0	0	0	0	0.000	1.000	30.604	10834	331563
Sum		6556911	155317889	1.000				

Table C.14: Lateral Force (in kN)

Storey	**IS 1893 Static - Y**	**IS 1893 Dynamic - Y**	**DBD - Y**
15	486	519	1086
14	543	506	1300
13	468	368	1207
12	399	267	1114
11	335	209	1021
10	277	186	928
9	224	178	835
8	177	174	743
7	136	171	650
6	100	170	557
5	69	168	464
4	44	156	371
3	25	124	278
2	11	77	186
1	3	28	93
0	0	0	0

Table C.15: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	486	519	1086
14	1029	1025	2386
13	1497	1393	3593
12	1896	1660	4707
11	2231	1870	5728
10	2508	2055	6656
9	2732	2234	7492
8	2910	2408	8234
7	3045	2579	8884
6	3145	2749	9441
5	3214	2917	9905
4	3259	3073	10277
3	3283	3197	10555
2	3295	3273	10741
1	3297	3301	10834
0	3297	3301	10834

Table C.16: Moment Distribution (in kN.m)

Storey	IS Static	IS Dynamic	DBD
15	0	0	0
14	1459	1556	3259
13	4546	4630	10417
12	9037	8809	21196
11	14725	13790	35316
10	21418	19398	52500
9	28942	25564	72469
8	37139	32265	94945
7	45867	39489	119648
6	55003	47226	146301
5	64438	55474	174625
4	74081	64225	204342
3	83856	73444	235172
2	93707	83034	266838
1	103590	92854	299061
0	113482	102758	331563

C.2 25 Storey building

C.2.1 X - Direction

Table C.17: Calculations Sheet

Building Data:		
No. Of storeys, n=	25	
Height of Building, H_n =	75	m
Zone Factor, Z=	0.36	
Assumed Effective Ht , H_e=	56.25	m
Beam Length, L_b=	5	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	5	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000913	per m
Design Displacement Profile:		
Wall Material strains:		
Damage control curvature, f_{dc}=	0.0144	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	Mpa
k	0.0337	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	2.60	m

Check if the code based drift limit is exceeded:		
θ_y=	0.0343	rad
θ_p=	0.0350	rad
θ_{cf}=	0.0694	rad
Code Based drift limit, θ_c	0.016	rad
Hence, Governing drift,θ_c=	0.016	rad
Governing θ_y=	0.016	rad
Governing θ_y=	0.000	rad
Drift limits:		
Drift Amplification Factor,ω_o=	0.950	
Reduced Design Drift,θ_r=	0.0152	rad
Reduced θ_y=	0.0152	rad
Reduced θ_p=	0.0000	rad
Δ_{yi}=	0.7620	m
Roof Level Design Displacement, Δ_d=	0.762	m
Design SDOF Displacement:		
Δ_d=	0.486	m
Effective Height:		
H_e=	55.62	m
Equivalent Damping:		
Yield Displ. of the SDOF substitute structure,Δ_{iy}=	0.486	m
Wall Displ. Ductility, μ_w=	1.00	
Wall Damping, ξ_w=	5.0000	%
Base Shear Force:		
Eff. Time Period, T_e=	3.39	sec
Eff. Mass, m_e=	6695580	kg
Eff. Stiffness, K_e=	22971	kN/m
Base Shear, V_b=	11174	kN

Table C.18: DBD Displacement Profile

Floor i	**Hi (m)**	**mi (kg)**	θ_{yi} **(rad)**	Δ_{yi} **(m)**	θ_{pi} **(rad)**	Δ_{pi} **(m)**	Δ_{di} **(m)**	**mi** Δ_{di}	**mi** Δ_{di}^2	**mi** Δ_{di} **Hi**
25	75	346106	0.0152	0.760	0.00	0.000	0.760	263041	199911	19728042
24	72	443629	0.0152	0.714	0.00	0.000	0.714	316939	226429	22819630
23	69	443629	0.0152	0.669	0.00	0.000	0.669	296785	198548	20478189
22	66	443629	0.0152	0.624	0.00	0.000	0.624	276761	172659	18266217
21	63	443629	0.0152	0.579	0.00	0.000	0.579	256931	148803	16186627
20	60	443629	0.0152	0.535	0.00	0.000	0.535	237359	126997	14241554
19	57	443629	0.0152	0.492	0.00	0.000	0.492	218112	107235	12432359
18	54	443629	0.0152	0.449	0.00	0.000	0.449	199252	89493	10759624
17	51	443629	0.0152	0.408	0.00	0.000	0.408	180846	73722	9223154
16	48	443629	0.0152	0.367	0.00	0.000	0.367	162958	59859	7821979
15	45	443629	0.0152	0.328	0.00	0.000	0.328	145652	47821	6554352
14	42	443629	0.0152	0.291	0.00	0.000	0.291	128994	37508	5417746
13	39	443629	0.0152	0.255	0.00	0.000	0.255	113048	28807	4408861
12	36	443629	0.0152	0.221	0.00	0.000	0.221	97878	21595	3523619
11	33	443629	0.0152	0.188	0.00	0.000	0.188	83550	15735	2757165
10	30	443629	0.0152	0.158	0.00	0.000	0.158	70129	11086	2103866
9	27	443629	0.0152	0.130	0.00	0.000	0.130	57678	7499	1557314
8	24	443629	0.0152	0.104	0.00	0.000	0.104	46263	4825	1110323
7	21	443629	0.0152	0.081	0.00	0.000	0.081	35949	2913	754932
6	18	443629	0.0152	0.060	0.00	0.000	0.060	26800	1619	482400
5	15	443629	0.0152	0.043	0.00	0.000	0.043	18881	804	283213
4	12	443629	0.0152	0.028	0.00	0.000	0.028	12256	339	147076
3	9	443629	0.0152	0.016	0.00	0.000	0.016	6991	110	62922
2	6	443629	0.0152	0.007	0.00	0.000	0.007	3150	22	18902
1	3	443629	0.0152	0.002	0.00	0.000	0.002	798	1	2395
0	0	0	0	0	0	0	0	0	0	0
Sum	0	10993201						3257004	1584340	181142463

Table C.19: Displacement Comparison(in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
25	106	76	760	760
24	103	73	714	714
23	99	71	669	669
22	96	68	624	624
21	92	66	579	579
20	88	63	535	535
19	83	60	492	492
18	79	57	449	449
17	74	54	408	408
16	69	50	367	367
15	64	47	328	328
14	58	44	291	291
13	53	40	255	255
12	48	36	221	221
11	42	33	188	188
10	37	29	158	158
9	32	25	130	130
8	26	21	104	104
7	21	17	81	81
6	17	14	60	60
5	12	10	43	43
4	8	7	28	28
3	5	4	16	16
2	3	2	7	7
1	1	1	2	2
0	0	0	0	0

Table C.20: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Drift - Yield	DBD Drift - Design
25	0.0011	0.0008	0.0152	0.01519
24	0.0012	0.0008	0.0151	0.01514
23	0.0012	0.0009	0.0150	0.01505
22	0.0013	0.0009	0.0149	0.01490
21	0.0014	0.0009	0.0147	0.01471
20	0.0015	0.0010	0.0145	0.01446
19	0.0015	0.0010	0.0142	0.01417
18	0.0016	0.0011	0.0138	0.01383
17	0.0017	0.0011	0.0134	0.01344
16	0.0017	0.0011	0.0130	0.01300
15	0.0017	0.0012	0.0125	0.01252
14	0.0018	0.0012	0.0120	0.01198
13	0.0018	0.0012	0.0114	0.01140
12	0.0018	0.0012	0.0108	0.01077
11	0.0018	0.0013	0.0101	0.01008
10	0.0018	0.0013	0.0094	0.00936
9	0.0017	0.0013	0.0086	0.00858
8	0.0017	0.0012	0.0077	0.00775
7	0.0016	0.0012	0.0069	0.00687
6	0.0015	0.0011	0.0060	0.00595
5	0.0013	0.0011	0.0050	0.00498
4	0.0011	0.0009	0.0040	0.00396
3	0.0009	0.0007	0.0029	0.00289
2	0.0006	0.0005	0.0018	0.00177
1	0.0002	0.0002	0.0006	0.00060
0	0.0000	0.0000	0.0000	0.00000

Table C.21: Shear Distribution (in kN)

Level	Height Hi (m)	Mass mi (kg)	miHi	$F_{i(relative)}$	$V_{i(relative)}$	$M_{i(relative)}$	V_i	M_i
25	75	346106	25957950	0.061	0.061	0.000	682	0
24	72	443629	31941284	0.075	0.136	0.183	1521	2046
23	69	443629	30610398	0.072	0.208	0.592	2326	6611
22	66	443629	29279511	0.069	0.277	1.216	3095	13588
21	63	443629	27948624	0.066	0.343	2.047	3830	22874
20	60	443629	26617737	0.063	0.405	3.075	4529	34363
19	57	443629	25286850	0.059	0.465	4.291	5194	47950
18	54	443629	23955963	0.056	0.521	5.686	5823	63531
17	51	443629	22625076	0.053	0.574	7.249	6418	81001
16	48	443629	21294190	0.050	0.624	8.972	6977	100254
15	45	443629	19963305	0.047	0.671	10.845	7502	121185
14	42	443629	18632416	0.044	0.715	12.859	7991	143691
13	39	443629	17301529	0.041	0.756	15.005	8446	167665
12	36	443629	15970642	0.038	0.793	17.273	8866	193003
11	33	443629	14639755	0.034	0.828	19.653	9250	219601
10	30	443629	13308869	0.031	0.859	22.136	9600	247352
9	27	443629	11977982	0.028	0.887	24.714	9915	276153
8	24	443629	10647095	0.025	0.912	27.376	10195	305897
7	21	443629	9316208	0.022	0.934	30.113	10440	336482
6	18	443629	7985321	0.019	0.953	32.916	10649	367800
5	15	443629	6654434	0.016	0.969	35.775	10824	399748
4	12	443629	5323547	0.013	0.981	38.681	10964	432221
3	9	443629	3992661	0.009	0.991	41.625	11069	465113
2	6	443629	2661774	0.006	0.997	44.597	11139	498320
1	3	443629	1330887	0.003	1.000	47.587	11174	531737
0	0	0	0	0.000	1.000	50.587	11174	565259
Sum		10993201	425224007	1.000				

Table C.22: Lateral Forces Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
25	387	522	682
24	416	489	839
23	382	378	804
22	349	281	769
21	318	206	734
20	289	154	699
19	261	122	664
18	234	100	630
17	209	83	595
16	185	69	560
15	162	61	525
14	141	63	490
13	122	74	455
12	104	91	420
11	87	108	385
10	72	121	350
9	58	130	315
8	46	139	280
7	35	147	245
6	26	151	210
5	18	146	175
4	12	126	140
3	6	93	105
2	3	53	70
1	1	18	35
0	0	0	0

Table C.23: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
25	387	522.02	682
24	803	1011.4	1521
23	1184	1389.01	2326
22	1534	1670.08	3095
21	1852	1876.24	3830
20	2140	2030.67	4529
19	2401	2152.25	5194
18	2635	2252.14	5823
17	2843	2335.14	6418
16	3028	2404.43	6977
15	3190	2465.89	7502
14	3332	2528.91	7991
13	3454	2603.19	8446
12	3558	2694.39	8866
11	3645	2802.36	9250
10	3717	2923.3	9600
9	3776	3053.75	9915
8	3822	3192.59	10195
7	3857	3339.37	10440
6	3883	3490.4	10649
5	3901	3636.12	10824
4	3913	3762.33	10964
3	3919	3855.32	11069
2	3922	3908.25	11139
1	3923	3925.82	11174

Table C.24: Moment Distribution (in kN.m)

Storey	IS Static	IS Dynamic	DBD
25	0	0	0
24	1161	1566	2046
23	3568	4600	6611
22	7121	8767	13588
21	11722	13778	22874
20	17277	19406	34363
19	23699	25498	47950
18	30902	31955	63531
17	38806	38711	81001
16	47336	45717	100254
15	56421	52930	121185
14	65992	60328	143691
13	75988	67915	167665
12	86349	75724	193003
11	97022	83807	219601
10	107958	92214	247352
9	119110	100984	276153
8	130437	110146	305897
7	141902	119723	336482
6	153474	129741	367800
5	165124	140213	399748
4	176828	151121	432221
3	188566	162408	465113
2	200324	173974	498320
1	212091	185699	531737
0	223859	197476	565259

C.2.2 Y - Direction

Table C.25: Calculations Sheet

Building Data:		
No. Of storeys, n=	25	
Height of Building, H_n =	75	m
Zone Factor, Z=	0.36	
Assumed Effective Ht , H_e=	56.25	m
Beam Length, Lb=	6	m
Beam depth,h_b=	0.6	m
Wall Length,l_w=	6	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000760833	per m
Design Displacement Profile:		
Wall Material strains:		
Damage control curvature, f_{dc}=	0.012	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	Mpa
k	0.0337	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	2.70	m

Check if the code based drift limit is exceeded:		
θ_y=	0.0286	rad
θ_p=	0.0303	rad
θ_{cf}=	0.0589	rad
Code Based drift limit, θ_{cf}	0.0160	rad
Hence, Governing drift, θ_c=	0.016	rad
Governing θ_y=	0.016	rad
Governing θ_p=	0.000	rad

Drift limits:		
Drift Amplification Factor, ω_o=	0.950	
Reduced Design Drift, θ_r=	0.0152	rad
Reduced θ_y=	0.0152	rad
Reduced θ_p=	0.0000	rad
Δ_{yi}=	0.7620	m
Roof Level Design Displacement, Δ_d=	0.762	m

Design SDOF Displacement:		
Δ_d=	0.486	

Effective Height:		
H_e=	55.62	m

Equivalent Damping:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.486	m
Wall Displ. Ductility, μ_w=	1.00	
Wall Damping, ξ_w=	5.0000	%

Base Shear Force:		
Eff. Time Period,T_e=	3.39	sec
Eff. Mass, m_e=	6695580	kg
Eff. Stiffness,K_e=	22971	kN/m
Base Shear, V_b=	11174	kN

Table C.26: DBD Displacement Profile

Floor i	**Hi (m)**	**mi (kg)**	θ_{yi} **(rad)**	Δ_{yi} **(m)**	θ_{pi} **(rad)**	Δ_{pi} **(m)**	Δ_{di} **(m)**	**mi** Δ_{di}	**mi** Δ_{di}^2	**mi** Δ_{di} **Hi**
25	75	346106	0.0152	0.760	0.00	0.000	0.760	263041	199911	19728042
24	72	443629	0.0152	0.714	0.00	0.000	0.714	316939	226429	22819630
23	69	443629	0.0152	0.669	0.00	0.000	0.669	296785	198548	20478189
22	66	443629	0.0152	0.624	0.00	0.000	0.624	276761	172659	18266217
21	63	443629	0.0152	0.579	0.00	0.000	0.579	256931	148803	16186627
20	60	443629	0.0152	0.535	0.00	0.000	0.535	237359	126997	14241554
19	57	443629	0.0152	0.492	0.00	0.000	0.492	218112	107235	12432359
18	54	443629	0.0152	0.449	0.00	0.000	0.449	199252	89493	10759624
17	51	443629	0.0152	0.408	0.00	0.000	0.408	180846	73722	9223154
16	48	443629	0.0152	0.367	0.00	0.000	0.367	162958	59859	7821979
15	45	443629	0.0152	0.328	0.00	0.000	0.328	145652	47821	6554352
14	42	443629	0.0152	0.291	0.00	0.000	0.291	128994	37508	5417746
13	39	443629	0.0152	0.255	0.00	0.000	0.255	113048	28807	4408861
12	36	443629	0.0152	0.221	0.00	0.000	0.221	97878	21595	3523619
11	33	443629	0.0152	0.188	0.00	0.000	0.188	83550	15735	2757165
10	30	443629	0.0152	0.158	0.00	0.000	0.158	70129	11086	2103866
9	27	443629	0.0152	0.130	0.00	0.000	0.130	57678	7499	1557314
8	24	443629	0.0152	0.104	0.00	0.000	0.104	46263	4825	1110323
7	21	443629	0.0152	0.081	0.00	0.000	0.081	35949	2913	754932
6	18	443629	0.0152	0.060	0.00	0.000	0.060	26800	1619	482400
5	15	443629	0.0152	0.043	0.00	0.000	0.043	18881	804	283213
4	12	443629	0.0152	0.028	0.00	0.000	0.028	12256	339	147076
3	9	443629	0.0152	0.016	0.00	0.000	0.016	6991	110	62922
2	6	443629	0.0152	0.007	0.00	0.000	0.007	3150	22	18902
1	3	443629	0.0152	0.002	0.00	0.000	0.002	798	1	2395
0	0	0	0	0	0	0	0	0	0	0
Sum	0	10993201						3257004	1584340	181142463

Table C.27: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
25	105	68	760	760
24	100	66	714	714
23	96	63	669	669
22	92	60	624	624
21	87	57	579	579
20	83	54	535	535
19	78	51	492	492
18	73	48	449	449
17	68	45	408	408
16	63	42	367	367
15	58	39	328	328
14	52	35	291	291
13	47	32	255	255
12	42	29	221	221
11	37	26	188	188
10	32	22	158	158
9	27	19	130	130
8	22	16	104	104
7	18	13	81	81
6	14	10	60	60
5	10	7	43	43
4	7	5	28	28
3	4	3	16	16
2	2	2	7	7
1	1	0	2	2
0	0	0	0	0

Table C.28: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
25	0.0014	0.0009	0.0152	0.0152
24	0.0014	0.0009	0.0151	0.0151
23	0.0015	0.0010	0.0150	0.0150
22	0.0015	0.0010	0.0149	0.0149
21	0.0016	0.0010	0.0147	0.0147
20	0.0016	0.0010	0.0145	0.0145
19	0.0016	0.0010	0.0142	0.0142
18	0.0017	0.0010	0.0138	0.0138
17	0.0017	0.0011	0.0134	0.0134
16	0.0017	0.0011	0.0130	0.0130
15	0.0017	0.0011	0.0125	0.0125
14	0.0017	0.0011	0.0120	0.0120
13	0.0017	0.0011	0.0114	0.0114
12	0.0017	0.0011	0.0108	0.0108
11	0.0017	0.0011	0.0101	0.0101
10	0.0016	0.0011	0.0094	0.0094
9	0.0016	0.0010	0.0086	0.0086
8	0.0015	0.0010	0.0077	0.0077
7	0.0014	0.0009	0.0069	0.0069
6	0.0012	0.0009	0.0060	0.0060
5	0.0011	0.0008	0.0050	0.0050
4	0.0009	0.0007	0.0040	0.0040
3	0.0007	0.0005	0.0029	0.0029
2	0.0005	0.0004	0.0018	0.0018
1	0.0002	0.0001	0.0006	0.0006
0	0.0000	0.0000	0.0000	0.0000

Table C.29: Shear Distribution(in kN)

Level	Height Hi (m)	Mass mi (kg)	miHi	$F_{i(relative)}$	$V_{i(relative)}$	$Mi(relative)$	V_i	M_i
25	75	346106	25957950	0.061	0.061	0.000	682	0
24	72	443629	31941284	0.075	0.136	0.183	1521	2046
23	69	443629	30610398	0.072	0.208	0.592	2326	6611
22	66	443629	29279511	0.069	0.277	1.216	3095	13588
21	63	443629	27948624	0.066	0.343	2.047	3830	22874
20	60	443629	26617737	0.063	0.405	3.075	4529	34363
19	57	443629	25286850	0.059	0.465	4.291	5194	47950
18	54	443629	23955963	0.056	0.521	5.686	5823	63531
17	51	443629	22625076	0.053	0.574	7.249	6418	81001
16	48	443629	21294190	0.050	0.624	8.972	6977	100254
15	45	443629	19963305	0.047	0.671	10.845	7502	121185
14	42	443629	18632416	0.044	0.715	12.859	7991	143691
13	39	443629	17301529	0.041	0.756	15.005	8446	167665
12	36	443629	15970642	0.038	0.793	17.273	8866	193003
11	33	443629	14639755	0.034	0.828	19.653	9250	219601
10	30	443629	13308869	0.031	0.859	22.136	9600	247352
9	27	443629	11977982	0.028	0.887	24.714	9915	276153
8	24	443629	10647095	0.025	0.912	27.376	10195	305897
7	21	443629	9316208	0.022	0.934	30.113	10440	336482
6	18	443629	7985321	0.019	0.953	32.916	10649	367800
5	15	443629	6654434	0.016	0.969	35.775	10824	399748
4	12	443629	5323547	0.013	0.981	38.681	10964	432221
3	9	443629	3992661	0.009	0.991	41.625	11069	465113
2	6	443629	2661774	0.006	0.997	44.597	11139	498320
1	3	443629	1330887	0.003	1.000	47.587	11174	531737
0	0	0	0	0.000	1.000	50.587	11174	565259
Sum		10993201	425224007	1.000				

Table C.30: Lateral Forces Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
25	328	452	682
24	353	430	839
23	324	335	804
22	297	247	769
21	270	169	734
20	245	107	699
19	221	62	664
18	199	36	630
17	177	27	595
16	157	30	560
15	138	39	525
14	120	51	490
13	104	64	455
12	88	79	420
11	74	97	385
10	61	118	350
9	50	139	315
8	39	156	280
7	30	163	245
6	22	157	210
5	15	139	175
4	10	109	140
3	6	74	105
2	2	40	70
1	1	13	35
0	0	0	0

Table C.31: Storey Shear Comparison (in kN)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD
25	328	452	682
24	681	882	1521
23	1006	1217	2326
22	1302	1464	3095
21	1572	1633	3830
20	1817	1740	4529
19	2039	1802	5194
18	2237	1838	5823
17	2414	1865	6418
16	2571	1895	6977
15	2709	1933	7502
14	2829	1984	7991
13	2933	2048	8446
12	3021	2126	8866
11	3095	2223	9250
10	3156	2341	9600
9	3206	2480	9915
8	3245	2635	10195
7	3275	2798	10440
6	3297	2956	10649
5	3312	3095	10824
4	3322	3204	10964
3	3328	3278	11069
2	3330	3318	11139
1	3331	3331	11174

Table C.32: Moment Distribution (in kN.m)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
25	0	0	0
24	985	1357	2046
23	3030	4003	6611
22	6046	7655	13588
21	9953	12047	22874
20	14670	16946	34363
19	20122	22166	47950
18	26237	27572	63531
17	32949	33087	81001
16	40191	38682	100254
15	47904	44365	121185
14	56031	50166	143691
13	64518	56118	167665
12	73315	62261	193003
11	82378	68639	219601
10	91662	75307	247352
9	101131	82329	276153
8	110748	89768	305897
7	120483	97674	336482
6	130308	106070	367800
5	140199	114938	399748
4	150137	124222	432221
3	160103	133834	465113
2	170086	143669	498320
1	180077	153624	531737
0	190069	163618	565259

Appendix D

Excel sheets - Wall-Frame buildings

D.1 15 Storeys - $\beta_F = 0.20$

D.1.1 X - Direction

Table D.1: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	5	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	5	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume β-frame=	0.2	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	37.81	m

Step3: Wall Yield Displacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000913	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.0144	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	MPa
k	0.0337	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.98	m
Check if the code based drift limit is exceeded:		
θ_{cf}=	0.044	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad
(b) Drift limits:		
Motm, frame=	9	kN.m per kN
Motm, wall=	21.786	kN.m per kN
Motm, total=	30.786	kN.m per kN
Drift Amplification Factor, ω_o=	0.946	
Reduced Design Drift, θ_r=	0.0189	rad
Design Displacment Profile: Given in "DBD Displacement Profile" Sheet		
Step5: Design SDOF Displacement:		
Δ_d=	0.419795537	
Step6: Effective Height:		
H_e=	33.25093358	m

Step7: Equivalent Damping:		
(a) Walls:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.357	m
Wall Displ. Ductility, μ_w=	1.18	
Wall Damping, ξ_w=	0.0712	
(b) Frames:		
Yield drift, θ_{yf}=	0.0095	rad
Frame Displ. Ductility, μ_f=	1.3275	
Frame Damping ratio, ξ_f=	0.0953	
System Damping, ξ_{sys}=	0.0783	
System Damping percentage, ξ_{sys}=	7.8264	%
Modification Factor for Damping, m.f.=	0.8725	
System ductility, μ_{sys}=	1.2208	
Step 8: Base Shear Force:		
Eff. Time Period, T_e=	3.13	sec
Eff. Mass, m_e=	3713161	kg
Eff. Stiffness, K_e=	14923	kN/m
Base Shear, V_b=	6265	kN

Table D.2: Calculation of Height of Contraflexure

Level	**Hi (m)**	**mi (kg)**	**mi.Hi (kg.m)**	$F_{i(relative)}$ **(kN)**	$V_{i(relative)}$ **(kN)**	$M_{i(relative)}$ **(kN.m)**	$V_{i,frame}$ **(kN)**	$V_{i,wall}$ **(kN)**	$M_{i,wall}$ **(kN.m)**	$M_{i,frame}$ **(kN.m)**
15	45	388230	17470350	0.113	0.113	0.000	0.2	-0.087	0.000	0.000
14	42	433640	18212880	0.118	0.231	0.339	0.2	0.031	-0.261	0.600
13	39	433640	16911960	0.110	0.341	1.032	0.2	0.141	-0.168	1.200
12	36	433640	15611040	0.101	0.442	2.055	0.2	0.242	0.255	1.800
11	33	433640	14310120	0.093	0.535	3.381	0.2	0.335	0.981	2.400
10	30	433640	13009200	0.084	0.619	4.986	0.2	0.419	1.986	3.000
9	27	433640	11708280	0.076	0.695	6.843	0.2	0.495	3.243	3.600
8	24	433640	10407360	0.068	0.763	8.928	0.2	0.563	4.728	4.200
7	21	433640	9106440	0.059	0.822	11.217	0.2	0.622	6.417	4.800
6	18	433640	7805520	0.051	0.873	13.683	0.2	0.673	8.283	5.400
5	15	433640	6504600	0.042	0.915	16.302	0.2	0.715	10.302	6.000
4	12	433640	5203680	0.034	0.949	19.047	0.2	0.749	12.447	6.600
3	9	433640	3902760	0.025	0.974	21.894	0.2	0.774	14.694	7.200
2	6	433640	2601840	0.017	0.991	24.816	0.2	0.791	17.016	7.800
1	3	433640	1300920	0.008	0.999	27.789	0.2	0.799	19.389	8.400
0	0	0	0	0.000	0.999	30.786	0.2	0.799	21.786	9.000
Sum		6459190	154066950	1.000						

Table D.3: DBD Displacement Profile

Level	**Height Hi (m)**	**Mass mi (kg)**	**Yield Displ. (m)**	**Design Displ. (m)**	**mi.**Δ_{di}^2 **(kg.**m^2**)**	**mi.**Δ_{di} **(kg.m)**	**mi.**Δ_{di}**.Hi (kg.**m^2**)**
15	45	348522	0.559	0.634	139945	220848	9938149
14	42	382926	0.507	0.577	127453	220919	9278591
13	39	382926	0.456	0.520	103614	199189	7768385
12	36	382926	0.404	0.463	82249	177469	6388883
11	33	382926	0.352	0.407	63473	155902	5144757
10	30	382926	0.302	0.352	47407	134735	4042040
9	27	382926	0.254	0.298	34068	114217	3083871
8	24	382926	0.207	0.247	23370	94600	2270393
7	21	382926	0.164	0.199	15136	76131	1598754
6	18	382926	0.124	0.154	9109	59061	1063106
5	15	382926	0.089	0.114	4973	43640	654603
4	12	382926	0.059	0.079	2369	30117	361406
3	9	382926	0.034	0.049	917	18742	168678
2	6	382926	0.016	0.025	249	9764	58585
1	3	382926	0.004	0.009	31	3434	10301
0	0	0	0.000	0.000	0	0	0
Sum		5709480			654364	1558768	51830501

Table D.4: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	55.3	44.3	559.2	633.7
14	51.9	41.7	507.4	576.9
13	48.4	39.0	455.6	520.2
12	44.5	36.0	403.8	463.5
11	40.5	32.9	352.5	407.1
10	36.2	29.6	302.2	351.9
9	31.7	26.1	253.6	298.3
8	27.1	22.5	207.3	247.0
7	22.4	18.9	164.0	198.8
6	17.9	15.2	124.4	154.2
5	13.5	11.6	89.1	114.0
4	9.4	8.2	58.8	78.7
3	5.8	5.1	34.0	48.9
2	2.9	2.6	15.6	25.5
1	0.9	0.8	4.0	9.0
0	0.0	0.0	0.0	0.0

Table D.5: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.0011	0.0009	0.0173	0.0189
14	0.0012	0.0009	0.0173	0.0189
13	0.0013	0.0010	0.0173	0.0189
12	0.0014	0.0010	0.0171	0.0188
11	0.0014	0.0011	0.0168	0.0184
10	0.0015	0.0012	0.0162	0.0179
9	0.0015	0.0012	0.0154	0.0171
8	0.0015	0.0012	0.0144	0.0161
7	0.0015	0.0012	0.0132	0.0149
6	0.0015	0.0012	0.0118	0.0134
5	0.0014	0.0011	0.0101	0.0118
4	0.0012	0.0010	0.0082	0.0099
3	0.0010	0.0008	0.0062	0.0078
2	0.0007	0.0006	0.0039	0.0055
1	0.0003	0.0003	0.0013	0.0030
0	0	0	0	0

Table D.6: Lateral Force Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	565	605	708
14	618	566	739
13	533	409	689
12	454	308	633
11	382	252	583
10	315	217	526
9	255	196	476
8	202	190	426
7	155	192	370
6	114	192	319
5	79	185	263
4	50	171	213
3	28	145	157
2	13	97	106
1	3	37	50
0	0	0	0

Table D.7: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	565	605	708
14	1183	1171	1447
13	1716	1580	2136
12	2170	1888	2769
11	2552	2140	3352
10	2867	2357	3878
9	3123	2552	4354
8	3324	2742	4780
7	3479	2934	5150
6	3592	3126	5469
5	3671	3311	5732
4	3722	3483	5945
3	3750	3628	6102
2	3763	3725	6208
1	3766	3762	6258
0	3766	3762	6258

Table D.8: Moment Distribution (in kN.m)

Storey	DBD - Frame	DBD - Wall	DBD - Total
15	0	0	0
14	3759	-1635	2124
13	7518	-1052	6465
12	11276	1597	12874
11	15035	6146	21181
10	18794	12442	31236
9	22553	20316	42869
8	26312	29619	55931
7	30070	40200	70271
6	33829	51890	85719
5	37588	64538	102126
4	41347	77976	119323
3	45105	92053	137158
2	48864	106599	155464
1	52623	121465	174088
0	56382	136482	192863

D.1.2 Y - Direction

Table D.9: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	6	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	6	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume β_{frame}=	0.2	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	37.83	m
Step3: Wall Yield Dislacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.00076083	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet:		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.012	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	MPa
k	0.03373494	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	2.08	m

Check if the code based drift limit is exceeded:		
θ_{cf}=	0.038	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad
(b) Drift limits:		
Motm,frame=	9	kN.m per kN
Motm,wall=	21.81	kN.m per kN
Motm,total=	30.81	kN.m per kN
Drift Amplification Factor, ω_o=	0.946	
Reduced Design Drift, θ_r=	0.0189	rad
Design Displacment Profile: Given in "DBD Displacement Profile" Sheet:		
Step5: Design SDOF Displacement:		
Δ_d=	0.44441589	m
Step6: Effective Height:		
H_e=	32.6538811	m
Step7: Equivalent Damping:		
(a) Walls:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.289	m
Wall Displ. Ductility, μ_w=	1.54	
Wall Damping, ξ_w=	0.0994	
(b) Frames:		
Yield drift, θ_{yf}=	0.0114125	rad
Frame Displ. Ductility, μ_f=	1.19254282	
Frame Damping ratio, ξ_f=	0.07965373	
System Damping, ξ_{sys}=	0.094	
System Damping percentage, ξ_{sys}=	9.367	%
Modification Factor for Damping, m.f. =	0.821	
System Ductility, μ_{sys}=	1.437	
Step 8: Base Shear Force:		
Eff. Time Period, T_e=	3.42	sec
Eff. Mass, m_e=	3887791	kg
Eff. Stiffness, K_e=	13121283.8	N/m
Base Shear, V_b=	5831	kN

Table D.10: Calculation of Height of Contraflexure

Level	Hi (m)	mi (kg)	mi.Hi (kg.m)	$F_{i(relative)}$ (kN)	$V_{i(relative)}$ (kN)	$M_{i(relative)}$ (kN.m)	$V_{i,frame}$ (kN)	$V_{i,wall}$ (kN)	$M_{i,wall}$ (kN.m)	$M_{i,frame}$ (kN.m)
15	45	388230	17470350	0.113	0.113	0.000	0.200	-0.087	0.000	0.000
14	42	433640	18212880	0.118	0.232	0.340	0.200	0.032	-0.260	0.600
13	39	433640	16911960	0.110	0.341	1.035	0.200	0.141	-0.165	1.200
12	36	433640	15611040	0.101	0.443	2.059	0.200	0.243	0.259	1.800
11	33	433640	14310120	0.093	0.536	3.387	0.200	0.336	0.987	2.400
10	30	433640	13009200	0.084	0.620	4.994	0.200	0.420	1.994	3.000
9	27	433640	11708280	0.076	0.696	6.854	0.200	0.496	3.254	3.600
8	24	433640	10407360	0.068	0.764	8.942	0.200	0.564	4.742	4.200
7	21	433640	9106440	0.059	0.823	11.233	0.200	0.623	6.433	4.800
6	18	433640	7805520	0.051	0.873	13.701	0.200	0.673	8.301	5.400
5	15	433640	6504600	0.042	0.916	16.321	0.200	0.716	10.321	6.000
4	12	433640	5203680	0.034	0.949	19.068	0.200	0.749	12.468	6.600
3	9	433640	3902760	0.025	0.975	21.916	0.200	0.775	14.716	7.200
2	6	433640	2601840	0.017	0.992	24.840	0.200	0.792	17.040	7.800
1	3	433640	1300920	0.008	1.000	27.814	0.200	0.800	19.414	8.400
0	0	0	0	0.000	1.000	30.814	0.200	0.800	21.814	9.000
Sum		6459190	154066950	1.000						

Table D.11: DBD Displacement Profile

Level	Height Hi (m)	Mass mi (kg)	Yield Displ. (m)	Design Displ. (m)	mi.Δ_{di}^2 (kg.m^2)	mi.Δ_{di} (kg.m)	mi.Δ_{di}.Hi (kg.m^2)
15	45	348522	0.466	0.670	156317	233409	10503423
14	42	382926	0.423	0.613	143875	234720	9858235
13	39	382926	0.380	0.556	118469	212990	8306601
12	36	382926	0.337	0.499	95536	191268	6885633
11	33	382926	0.294	0.443	75183	169674	5599258
10	30	382926	0.252	0.388	57524	148416	4452490
9	27	382926	0.211	0.333	42587	127701	3447928
8	24	382926	0.173	0.281	30312	107737	2585678
7	21	382926	0.137	0.232	20561	88731	1863347
6	18	382926	0.104	0.185	13124	70892	1276051
5	15	382926	0.074	0.142	7736	54427	816407
4	12	382926	0.049	0.103	4084	39545	474541
3	9	382926	0.028	0.069	1827	26453	238081
2	6	382926	0.013	0.040	616	15360	92160
1	3	382926	0.003	0.017	109	6473	19419
0	0	0	0.000	0.000	0	0	0
Sum		5709480.122			767860	1727796	56419250

Table D.12: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	49.5	38.8	466.2	669.7
14	45.9	35.9	423.0	613.0
13	42.1	33.1	379.8	556.2
12	38.2	30.1	336.6	499.5
11	34.2	27	293.8	443.1
10	30.1	23.9	251.9	387.6
9	26	20.8	211.4	333.5
8	21.9	17.6	172.8	281.4
7	17.9	14.5	136.7	231.7
6	14	11.4	103.7	185.1
5	10.4	8.6	74.3	142.1
4	7.1	5.9	49.0	103.3
3	4.3	3.7	28.4	69.1
2	2.1	1.8	13.0	40.1
1	0.6	0.5	3.3	16.9
0	0.0	0.0	0.0	0.0

Table D.13: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.001222	0.00096	0.01439	0.01892
14	0.001257	0.000988	0.01439	0.01892
13	0.001295	0.001017	0.01439	0.01891
12	0.001331	0.001043	0.01427	0.01880
11	0.001359	0.001063	0.01398	0.01851
10	0.001373	0.001074	0.01351	0.01803
9	0.001368	0.001072	0.01286	0.01738
8	0.001341	0.001055	0.01202	0.01654
7	0.001288	0.00102	0.01101	0.01553
6	0.001204	0.000963	0.00981	0.01433
5	0.001088	0.00088	0.00843	0.01295
4	0.000934	0.000766	0.00687	0.01140
3	0.000739	0.000616	0.00513	0.00966
2	0.000499	0.000423	0.00321	0.00774
1	0.000206	0.000179	0.00111	0.00563
0	0	0	0	0

Table D.14: Lateral Force Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	479.2	523.28	661
14	524.27	493.7	689
13	452.04	350.26	640
12	385.17	244.8	591
11	323.66	185.34	542
10	267.48	163.49	492
9	216.66	160.22	443
8	171.19	160.88	394
7	131.06	162.56	345
6	96.3	167.26	295
5	66.87	170.92	246
4	42.79	162.05	197
3	24.08	131.3	148
2	10.7	81.67	98
1	2.67	29.87	49
0	0	0	0

Table D.15: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	479	523	661
14	1003	1017	1351
13	1456	1367	1991
12	1841	1612	2582
11	2164	1797	3123
10	2432	1961	3616
9	2648	2121	4059
8	2820	2282	4453
7	2951	2445	4797
6	3047	2612	5093
5	3114	2783	5339
4	3157	2945	5536
3	3181	3076	5684
2	3191	3158	5782
1	3194	3188	5831
0	3194	3188	5831

Table D.16: Moment Distribution (in kN.m)

Storey	**DBD - Frame**	**DBD - Wall**	**DBD - Total**
15	0	0	0
14	3499	-1515	1984
13	6998	-962	6035
12	10496	1511	12008
11	13995	5757	19752
10	17494	11628	29122
9	20993	18976	39968
8	24491	27653	52145
7	27990	37512	65502
6	31489	48405	79894
5	34988	60185	95172
4	38487	72703	111189
3	41985	85811	127797
2	45484	99363	144848
1	48983	113211	162194
0	52482	127206	179688

D.2 15 Storeys - $\beta_F = 0.30$

D.2.1 X - Direction

Table D.17: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	5	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	5	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume -frame=	0.3	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	32.10	m
Step3: Wall Yield Dislacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000913	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet:		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.0144	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	MPa
k	0.0337349	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.78	m

Check if the code based drift limit is exceeded:		
θ_{cf}=	0.039	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad
(b) Drift limits:		
Motm, frame=	13.5	kN.m per kN
Motm, wall=	17.314313	kN.m per kN
Motm, total=	30.814313	kN.m per kN
Drift Amplification Factor, ω_o=	0.931	
Reduced Design Drift, θ_r=	0.0186	rad
Design Displacment Profile: Given in "DBD Displacement Profile" Sheet:		
Step5: Design SDOF Displacement:		
Δ_d=	0.4556972	m
Step6: Effective Height:		
H_e=	32.633523	m
Step7: Equivalent Damping:		
(a) Walls:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.321	m
Wall Displ. Ductility, μ_w=	1.42	
Wall Damping, ξ_w=	0.0917	
(b) Frames:		
Yield drift, θ_{yf}=	0.0095104	rad
Frame Displ. Ductility, μ_f=	1.4682935	
Frame Damping ratio, ξ_f=	0.1085776	
System Damping, ξ_{sys}=	0.0990682	
System Damping percentage, ξ_{sys}=	9.9068187	%
Modification Factor for Damping, m.f.=	0.803106	
System ductility=	1.4399732	
Step 8: Base Shear Force:		
Eff. Time Period, T_e=	3.55	sec
Eff. Mass, m_e=	3896056	kg
Eff. Stiffness, K_e=	12231912	N/m
Base Shear, V_b=	5574	kN

Table D.18: Calculation of Height of Contraflexure

Level	Hi (m)	mi (kg)	mi.Hi (kg.m)	$F_{i(relative)}$ (kN)	$V_{i(relative)}$ (kN)	$M_{i(relative)}$ (kN.m)	$V_{i,frame}$ (kN)	$V_{i,wall}$ (kN)	$M_{i,wall}$ (kN.m)	$M_{i,frame}$ (kN.m)
15	45	388230	17470350	0.113	0.113	0.000	0.300	-0.187	0.000	0.000
14	42	433640	18212880	0.118	0.232	0.340	0.300	-0.068	-0.560	0.900
13	39	433640	16911960	0.110	0.341	1.035	0.300	0.041	-0.765	1.800
12	36	433640	15611040	0.101	0.443	2.059	0.300	0.143	-0.641	2.700
11	33	433640	14310120	0.093	0.536	3.387	0.300	0.236	-0.213	3.600
10	30	433640	13009200	0.084	0.620	4.994	0.300	0.320	0.494	4.500
9	27	433640	11708280	0.076	0.696	6.854	0.300	0.396	1.454	5.400
8	24	433640	10407360	0.068	0.764	8.942	0.300	0.464	2.642	6.300
7	21	433640	9106440	0.059	0.823	11.233	0.300	0.523	4.033	7.200
6	18	433640	7805520	0.051	0.873	13.701	0.300	0.573	5.601	8.100
5	15	433640	6504600	0.042	0.916	16.321	0.300	0.616	7.321	9.000
4	12	433640	5203680	0.034	0.949	19.068	0.300	0.649	9.168	9.900
3	9	433640	3902760	0.025	0.975	21.916	0.300	0.675	11.116	10.800
2	6	433640	2601840	0.017	0.992	24.840	0.300	0.692	13.140	11.700
1	3	433640	1300920	0.008	1.000	27.814	0.300	0.700	15.214	12.600
0	0	0	0	0.000	1.000	30.814	0.300	0.700	17.314	13.500
Sum		6459190	154066950	1.000						

Table D.19: DBD Displacement Profile

Level	Height Hi (m)	Mass mi (kg)	Yield Displ. (m)	Design Displ. (m)	mi.Δ_{di}^2 (kg.m^2)	mi.Δ_{di} (kg.m)	mi.Δ_{di}.Hi (kg.m^2)
15	45	348522	0.503	0.681	161776	237450	10685248
14	42	382926	0.459	0.625	149788	239495	10058781
13	39	382926	0.415	0.570	124222	218100	8505909
12	36	382926	0.371	0.514	101046	196706	7081404
11	33	382926	0.327	0.458	80261	175311	5785266
10	30	382926	0.283	0.402	61880	153933	4617998
9	27	382926	0.239	0.347	46029	132762	3584583
8	24	382926	0.197	0.293	32812	112091	2690186
7	21	382926	0.157	0.241	22206	92214	1936485
6	18	382926	0.120	0.192	14079	73424	1321630
5	15	382926	0.087	0.146	8194	56016	840243
4	12	382926	0.058	0.105	4238	40285	483414
3	9	382926	0.034	0.069	1837	26523	238707
2	6	382926	0.015	0.039	590	15026	90154
1	3	382926	0.004	0.016	97	6087	18260
0	0	0	0.000	0.000	0	0	0
Sum		5709480			809055	1775422	57938267

Table D.20: Displacement Comparison (in mm)

Storeys	**IS 1893 Static**	**IS 1893 Dynamic**	**DBD Yield**	**DBD Design**
15	55.3	44.3	502.6	681.3
14	51.9	41.7	458.6	625.4
13	48.4	39.0	414.7	569.6
12	44.5	36.0	370.7	513.7
11	40.5	32.9	326.8	457.8
10	36.2	29.6	282.8	402.0
9	31.7	26.1	239.5	346.7
8	27.1	22.5	197.4	292.7
7	22.4	18.9	157.4	240.8
6	17.9	15.2	120.3	191.7
5	13.5	11.6	86.7	146.3
4	9.4	8.2	57.5	105.2
3	5.8	5.1	33.5	69.3
2	2.9	2.6	15.4	39.2
1	0.9	0.8	4.0	15.9
0	0.0	0.0	0.0	0.0

Table D.21: Drift Comparison

Storeys	**IS 1893 Static**	**IS 1893 Dynamic**	**DBD - Yield**	**DBD - Design**
15	0.00113	0.00087	0.01465	0.01862
14	0.00119	0.00092	0.01465	0.01862
13	0.00127	0.00097	0.01465	0.01862
12	0.00136	0.00104	0.01465	0.01862
11	0.00143	0.00110	0.01464	0.01861
10	0.00150	0.00116	0.01446	0.01843
9	0.00153	0.00120	0.01402	0.01799
8	0.00155	0.00123	0.01333	0.01730
7	0.00153	0.00123	0.01238	0.01636
6	0.00146	0.00120	0.01118	0.01515
5	0.00136	0.00114	0.00972	0.01369
4	0.00120	0.00102	0.00801	0.01198
3	0.00097	0.00085	0.00604	0.01001
2	0.00068	0.00060	0.00381	0.00778
1	0.00028	0.00026	0.00133	0.00530
0	0	0	0	0

Table D.22: Lateral Force Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	565	605	632
14	618	566	659
13	533	409	612
12	454	308	565
11	382	252	518
10	315	217	471
9	255	196	424
8	202	190	377
7	155	192	329
6	114	192	282
5	79	185	235
4	50	171	188
3	28	145	141
2	13	97	94
1	3	37	47
0	0	0	0

Table D.23: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	565	605	632
14	1183	1171	1291
13	1716	1580	1903
12	2170	1888	2468
11	2552	2140	2985
10	2867	2357	3456
9	3123	2552	3880
8	3324	2742	4256
7	3479	2934	4586
6	3592	3126	4868
5	3671	3311	5103
4	3722	3483	5292
3	3750	3628	5433
2	3763	3725	5527
1	3766	3762	5574
0	3766	3762	5574

Table D.24: Moment Distribution (in kN.m)

Storey	**DBD - Frame**	**DBD - Wall**	**DBD - Total**
15	0	0	0
14	5017	-3120	1896
13	10033	-4264	5769
12	15050	-3572	11478
11	20067	-1186	18881
10	25083	2754	27837
9	30100	8105	38205
8	35117	14728	49844
7	40133	22479	62613
6	45150	31220	76370
5	50166	40807	90974
4	55183	51101	106284
3	60200	61959	122159
2	65216	73241	138457
1	70233	84805	155038
0	75250	96511	171760

D.2.2 Y - Direction

Table D.25: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	6	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	6	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume β_{frame}=	0.3	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	32.10	m
Step3: Wall Yield Dislacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.00076083	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet:		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.012	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	Mpa
k	0.03373494	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.88	m

Check if the code based drift limit is exceeded:		
θ_{cf}=	0.033	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad
(b) Drift limits:		
Motm, frame=	13.5	kN.m per kN
Motm, wall=	17.3143125	kN.m per kN
Motm, total=	30.8143125	kN.m per kN
Drift Amplification Factor, ω_o=	0.931	
Reduced Design Drift, θ_r=	0.0186	rad
Design Displacment Profile: Given in "DBD Displacement Profile" Sheet:		
Step5: Design SDOF Displacement:		
Δ_d=	0.47409801	m
Step6: Effective Height:		
H_e=	32.23	m
Step7: Equivalent Damping:		
(a) Walls:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.26	m
Wall Displ. Ductility, μ_w=	1.80	
Wall Damping, ξ_w=	0.11	
(b) Frames:		
Yield drift, θ_{yf}=	0.01	rad
Frame Displ. Ductility, μ_f=	1.29	
Frame Damping ratio, ξ_f=	0.09	
System Damping, ξ_{sys}=	0.10	
System Damping percentage, ξ_{sys}=	10.34	%
Modification Factor for Damping, m.f. =	0.79	
System Ductility, μ_{sys}=	1.58	
Step 8: Base Shear Force:		
Eff. Time Period, T_e=	3.71	sec
Eff. Mass, m_e=	4012911	kg
Eff. Stiffness, K_e=	11496386	N/m
Base Shear, V_b=	5450	kN

Table D.26: Calculation of Height of Contraflexure

Level	**Hi (m)**	**mi (kg)**	**mi.Hi (kg.m)**	$F_{i(relative)}$ **(kN)**	$V_{i(relative)}$ **(kN)**	$M_{i(relative)}$ **(kN.m)**	$V_{i,frame}$ **(kN)**	$V_{i,wall}$ **(kN)**	$M_{i,wall}$ **(kN.m)**	$M_{i,frame}$ **(kN.m)**
15	45	388230	17470350	0.113	0.113	0.000	0.300	-0.187	0.000	0.000
14	42	433640	18212880	0.118	0.232	0.340	0.300	-0.068	-0.560	0.900
13	39	433640	16911960	0.110	0.341	1.035	0.300	0.041	-0.765	1.800
12	36	433640	15611040	0.101	0.443	2.059	0.300	0.143	-0.641	2.700
11	33	433640	14310120	0.093	0.536	3.387	0.300	0.236	-0.213	3.600
10	30	433640	13009200	0.084	0.620	4.994	0.300	0.320	0.494	4.500
9	27	433640	11708280	0.076	0.696	6.854	0.300	0.396	1.454	5.400
8	24	433640	10407360	0.068	0.764	8.942	0.300	0.464	2.642	6.300
7	21	433640	9106440	0.059	0.823	11.233	0.300	0.523	4.033	7.200
6	18	433640	7805520	0.051	0.873	13.701	0.300	0.573	5.601	8.100
5	15	433640	6504600	0.042	0.916	16.321	0.300	0.616	7.321	9.000
4	12	433640	5203680	0.034	0.949	19.068	0.300	0.649	9.168	9.900
3	9	433640	3902760	0.025	0.975	21.916	0.300	0.675	11.116	10.800
2	6	433640	2601840	0.017	0.992	24.840	0.300	0.692	13.140	11.700
1	3	433640	1300920	0.008	1.000	27.814	0.300	0.700	15.214	12.600
0	0	0	0	0.000	1.000	30.814	0.300	0.700	17.314	13.500
Sum		6459190	154066950	1.000						

Table D.27: DBD Displacement Profile

Level	**Height Hi (m)**	**Mass mi (kg)**	**Yield Displ. (m)**	**Design Displ. (m)**	**mi.**Δ_{di}^2 **(kg.**m^2**)**	**mi.**Δ_{di} **(kg.m)**	**mi.**Δ_{di}**.Hi (kg.**m^2**)**
15	45	348522	0.419	0.707	174422	246556	11095017
14	42	382926	0.382	0.652	162564	249500	10478986
13	39	382926	0.346	0.596	135880	228105	8896099
12	36	382926	0.309	0.540	111489	206621	7438341
11	33	382926	0.272	0.484	89682	185315	6115390
10	30	382926	0.236	0.428	70183	163935	4918060
9	27	382926	0.200	0.373	53198	142727	3853633
8	24	382926	0.165	0.318	38828	121935	2926448
7	21	382926	0.131	0.266	27066	101805	2137904
6	18	382926	0.100	0.216	17809	82581	1486461
5	15	382926	0.072	0.168	10867	64509	967635
4	12	382926	0.048	0.125	5975	47833	574002
3	9	382926	0.028	0.086	2809	32800	295198
2	6	382926	0.013	0.051	1009	19653	117917
1	3	382926	0.003	0.023	195	8638	25914
0	0	0	0.000	0.000	0	0	0
Sum		5709480			901978	1902513	61327002

Table D.28: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	49.5	38.8	418.8	707.4
14	45.9	35.9	382.2	651.6
13	42.1	33.1	345.6	595.7
12	38.2	30.1	308.7	539.6
11	34.2	27	272.3	483.9
10	30.1	23.9	235.7	428.1
9	26	20.8	199.6	372.7
8	21.9	17.6	164.5	318.4
7	17.9	14.5	131.2	265.9
6	14	11.4	100.2	215.7
5	10.4	8.6	72.3	168.5
4	7.1	5.9	48.0	124.9
3	4.3	3.7	27.9	85.7
2	2.1	1.8	12.8	51.3
1	0.6	0.5	3.3	22.6
0	0.0	0.0	0.0	0.0

Table D.29: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.001222	0.00096	0.01221	0.01862
14	0.001257	0.000988	0.01221	0.01862
13	0.001295	0.001017	0.01229	0.01870
12	0.001331	0.001043	0.01213	0.01855
11	0.001359	0.001063	0.01220	0.01861
10	0.001373	0.001074	0.01205	0.01846
9	0.001368	0.001072	0.01169	0.01810
8	0.001341	0.001055	0.01111	0.01752
7	0.001288	0.00102	0.01032	0.01673
6	0.001204	0.000963	0.00932	0.01573
5	0.001088	0.00088	0.00810	0.01452
4	0.000934	0.000766	0.00667	0.01309
3	0.000739	0.000616	0.00503	0.01144
2	0.000499	0.000423	0.00317	0.00959
1	0.000206	0.000179	0.00111	0.00752
0	0	0	0	0

Table D.30: Lateral Forces Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	479.2	523.28	618.0
14	524.27	493.7	644.3
13	452.04	350.26	598.3
12	385.17	244.8	552.3
11	323.66	185.34	506.2
10	267.48	163.49	460.2
9	216.66	160.22	414.2
8	171.19	160.88	368.2
7	131.06	162.56	322.2
6	96.3	167.26	276.1
5	66.87	170.92	230.1
4	42.79	162.05	184.1
3	24.08	131.3	138.1
2	10.7	81.67	92.0
1	2.67	29.87	46.0
0	0	0	0

Table D.31: Storey Shear Comparison (in kN)

Storey	Static - Base shear	Dynamic-Base shear	DBD- Base Shear
15	479	523	618
14	1003	1017	1262
13	1456	1367	1861
12	1841	1612	2413
11	2164	1797	2919
10	2432	1961	3379
9	2648	2121	3794
8	2820	2282	4162
7	2951	2445	4484
6	3047	2612	4760
5	3114	2783	4990
4	3157	2945	5174
3	3181	3076	5312
2	3191	3158	5404
1	3194	3188	5450
0	3194	3188	5450

Table D.32: Moment Distribution (in kN.m)

Storey	**DBD - Frame**	**DBD - Wall**	**DBD - Total**
15	0	0	0
14	4905	-3051	1854
13	9811	-4170	5641
12	14716	-3493	11223
11	19621	-1160	18462
10	24527	2693	27219
9	29432	7925	37358
8	34338	14401	48739
7	39243	21981	61224
6	44148	30527	74676
5	49054	39902	88956
4	53959	49967	103926
3	58864	60585	119449
2	63770	71616	135386
1	68675	82924	151600
0	73581	94370	167951

D.3 15 Storeys - $\beta_F = 0.40$

D.3.1 X - Direction

Table D.33: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	5	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	5	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume β_{frame}=	0.4	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	25.83	m
Step3: Wall Yield Dislacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.000913	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet:		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.0144	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	Mpa
k	0.0337349	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.57	m

Check if the code based drift limit is exceeded:		
θ_{cf}=	0.033	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad
(b) Drift limits:		
Motm, frame=	18	kN.m per kN
Motm, wall=	12.814313	kN.m per kN
Motm, total=	30.814313	kN.m per kN
Drift Amplification Factor, ω_o=	0.917	
Reduced Design Drift, θ_r=	0.0183	rad

Design Displacment Profile: Given in "DBD Displacement Profile" Sheet:

Step5: Design SDOF Displacement:		
Δ_d=	0.4885501	m
Step6: Effective Height:		
H_e=	32.073324	m
Step7: Equivalent Damping:		
(a) Walls:		
Yield Displ. of the SDOF substitute structure, Δ_{iy}=	0.277	m
Wall Displ. Ductility, μ_w=	1.77	
Wall Damping, ξ_w=	0.1113	
(b) Frames:		
Yield drift, θ_{yf}=	0.010	rad
Frame Displ. Ductility, μ_f=	1.602	
Frame Damping ratio, ξ_f=	0.119	
System Damping, ξ_{sys}=	0.116	
System Damping percentage, ξ_{sys}=	11.579	%
Modification Factor for Damping, m.f.=	0.768	
System Ductility, μ_{sys}=	1.670	
Step 8: Base Shear Force:		
Eff. Time Period, T_e=	3.89	sec
Eff. Mass, m_e=	4061757	kg
Eff. Stiffness, K_e=	10615578	N/m
Base Shear, V_b=	5186	kN

Table D.34: Calculation of Height of Contraflexure

Level	**Hi (m)**	**mi (kg)**	**mi.Hi (kg.m)**	$F_{i(relative)}$ **(kN)**	$V_{i(relative)}$ **(kN)**	$M_{i(relative)}$ **(kN.m)**	$V_{i,frame}$ **(kN)**	$V_{i,wall}$ **(kN)**	$M_{i,wall}$ **(kN.m)**	$M_{i,frame}$ **(kN.m)**
15	45	388230	17470350	0.113	0.113	0.000	0.400	-0.287	0.000	0.000
14	42	433640	18212880	0.118	0.232	0.340	0.400	-0.168	-0.860	1.200
13	39	433640	16911960	0.110	0.341	1.035	0.400	-0.059	-1.365	2.400
12	36	433640	15611040	0.101	0.443	2.059	0.400	0.043	-1.541	3.600
11	33	433640	14310120	0.093	0.536	3.387	0.400	0.136	-1.413	4.800
10	30	433640	13009200	0.084	0.620	4.994	0.400	0.220	-1.006	6.000
9	27	433640	11708280	0.076	0.696	6.854	0.400	0.296	-0.346	7.200
8	24	433640	10407360	0.068	0.764	8.942	0.400	0.364	0.542	8.400
7	21	433640	9106440	0.059	0.823	11.233	0.400	0.423	1.633	9.600
6	18	433640	7805520	0.051	0.873	13.701	0.400	0.473	2.901	10.800
5	15	433640	6504600	0.042	0.916	16.321	0.400	0.516	4.321	12.000
4	12	433640	5203680	0.034	0.949	19.068	0.400	0.549	5.868	13.200
3	9	433640	3902760	0.025	0.975	21.916	0.400	0.575	7.516	14.400
2	6	433640	2601840	0.017	0.992	24.840	0.400	0.592	9.240	15.600
1	3	433640	1300920	0.008	1.000	27.814	0.400	0.600	11.014	16.800
0	0	0	0	0.000	1.000	30.814	0.400	0.600	12.814	18.000
Sum		6459190	154066950	1.000						

Table D.35: DBD Displacement Profile

Level	**Height Hi (m)**	**Mass mi (kg)**	**Yield Displ. (m)**	**Design Displ. (m)**	**mi.**Δ_{di}^2 **(kg.**m^2**)**	**mi.**Δ_{di} **(kg.m)**	**mi.**Δ_{di}**.Hi (kg.**m^2**)**
15	45	348522	0.429	0.723	182380	252118	11345297
14	42	382926	0.394	0.668	171073	255946	10749731
13	39	382926	0.358	0.613	144080	234887	9160590
12	36	382926	0.323	0.558	119403	213828	7697804
11	33	382926	0.288	0.503	97042	192769	6361372
10	30	382926	0.252	0.448	76997	171710	5151294
9	27	382926	0.217	0.393	59269	150651	4067570
8	24	382926	0.182	0.338	43866	129606	3110533
7	21	382926	0.147	0.284	30906	108787	2284528
6	18	382926	0.114	0.231	20480	88557	1594028
5	15	382926	0.083	0.181	12535	69281	1039216
4	12	382926	0.056	0.134	6879	51324	615893
3	9	382926	0.033	0.092	3209	35053	315473
2	6	382926	0.015	0.054	1133	20831	124985
1	3	382926	0.004	0.024	213	9025	27075
0	0	0	0.000	0.000	0	0	0
Sum		5709480.122			969465	1984371	63645388

Table D.36: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	55.3	44.3	429.1	723.4
14	51.9	41.7	393.7	668.4
13	48.4	39.0	358.4	613.4
12	44.5	36.0	323.0	558.4
11	40.5	32.9	287.6	503.4
10	36.2	29.6	252.2	448.4
9	31.7	26.1	216.9	393.4
8	27.1	22.5	181.5	338.5
7	22.4	18.9	146.8	284.1
6	17.9	15.2	113.6	231.3
5	13.5	11.6	82.8	180.9
4	9.4	8.2	55.6	134.0
3	5.8	5.1	32.7	91.5
2	2.9	2.6	15.2	54.4
1	0.9	0.8	3.9	23.6
0	0.0	0.0	0.0	0.0

Table D.37: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.00113	0.00087	0.01179	0.01833
14	0.00119	0.00092	0.01179	0.01833
13	0.00127	0.00097	0.01179	0.01833
12	0.00136	0.00104	0.01179	0.01833
11	0.00143	0.00110	0.01179	0.01833
10	0.00150	0.00116	0.01179	0.01833
9	0.00153	0.00120	0.01178	0.01832
8	0.00155	0.00123	0.01158	0.01812
7	0.00153	0.00123	0.01107	0.01761
6	0.00146	0.00120	0.01024	0.01678
5	0.00136	0.00114	0.00909	0.01563
4	0.00120	0.00102	0.00762	0.01416
3	0.00097	0.00085	0.00584	0.01238
2	0.00068	0.00060	0.00374	0.01028
1	0.00028	0.00026	0.00132	0.00786
0	0	0	0	0

Table D.38: Lateral Force Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	564.99	604.77	588.0913894
14	618.11	565.8	613.0866242
13	532.96	409.4	569.2947225
12	454.13	308.28	525.5028207
11	381.59	251.57	481.710919
10	315.36	216.85	437.9190173
9	255.45	195.62	394.1271155
8	201.83	189.55	350.3352138
7	154.53	192.42	306.5433121
6	113.53	192.12	262.7514104
5	78.84	184.78	218.9595086
4	50.46	171.49	175.1676069
3	28.38	145.23	131.3757052
2	12.62	96.98	87.58380345
1	3.15	37.11	43.79190173
0	0	0	0

Table D.39: Storey Shear Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	565	605	588
14	1183	1171	1201
13	1716	1580	1770
12	2170	1888	2296
11	2552	2140	2778
10	2867	2357	3216
9	3123	2552	3610
8	3324	2742	3960
7	3479	2934	4267
6	3592	3126	4529
5	3671	3311	4748
4	3722	3483	4923
3	3750	3628	5055
2	3763	3725	5142
1	3766	3762	5186
0	3766	3762	5186

Table D.40: Moment Distribution (in kN.m)

Storey	**DBD - Frame**	**DBD - Wall**	**DBD - Total**
15	0	0	0
14	6223	-4459	1764
13	12447	-7079	5368
12	18670	-7991	10679
11	24894	-7327	17567
10	31117	-5217	25900
9	37341	-1794	35547
8	43564	2812	46376
7	49788	8469	58256
6	56011	15045	71056
5	62235	22409	84644
4	68458	30431	98889
3	74682	38978	113660
2	80905	47919	128824
1	87129	57123	144252
0	93352	66458	159810

D.3.2 Y - Direction

Table D.41: Calculations Sheet

Building Data:		
No. Of storeys, n=	15	
Zone Factor, Z=	0.36	
Beam Length, L_b=	6	m
Beam depth, h_b=	0.6	m
Wall Length, l_w=	6	m
f_y=	415	MPa
f_{ye}=	456.5	MPa
Step 1: Design Choices:		
Assume β_{frame} =	0.4	
Step2: Wall Contraflexure height:		
Ht of contralexure, H_{cf}=	25.83	m
Step3: Wall Yield Dislacement:		
Reinforcement steel yield strain, ε_y	0.0022825	
Yield curvature, f_y=	0.0007608	per m
Yield Displacement Profile: Given in "DBD Displacement Profile" Sheet:		
Step4: Design Displacement Profile:		
(a) Wall Material strains:		
Damage control curvature, f_{dc}=	0.012	per m
Plastic hinge length:		
for Fe 415 as per IS 1786 : 1985, f_u=	485	Mpa
k	0.0337349	
Assume diameter of Longi. Reinfo., d_{bl}=	20	
Strain Penetration Length, L_{sp}=	200.86	mm
Plastic hinge length, L_p=	1.67	m
Check if the code based drift limit is exceeded:		
θ_{cf}=	0.029	rad
Code Based drift limit, θ_c	0.02	rad
Hence, Governing drift, θ_c=	0.02	rad

(b) Drift limits:		
Motm, frame=	18	kN.m per kN
Motm, wall=	12.814313	kN.m per kN
Motm, total=	30.814313	kN.m per kN
Drift Amplification Factor, ω_o=	0.917	
Reduced Design Drift, θ_r=	0.0183	rad

Design Displacment Profile: Given in "DBD Displacement Profile" Sheet:

Step5: Design SDOF Displacement:

Δ_d=	0.5007368	m

Step6: Effective Height:

H_e=	31.825409	m

Step7: Equivalent Damping:

(a) Walls:		
Yield Displ. of the SDOF substitute structure, δ_{iy}=	0.228	m
Wall Displ. Ductility, μ_w=	2.19	
Wall Damping, ξ_w=	0.1269	
(b) Frames:		
Yield drift, θ_{yf}=	0.0114125	rad
Frame Displ. Ductility, μ_f=	1.3786523	
Frame Damping ratio, ξ_f=	0.1004443	
System Damping, ξ_{sys}=	0.1114636	
System Damping percentage, ξ_{sys}=	11.146365	%
Modification Factor for Damping, m.f. =	0.7770727	
System Ductility, μ_{sys}=	1.7181326	

Step 8: Base Shear Force:

Eff. Time Period, T_e=	3.96	sec
Eff. Mass, m_e=	4134095	kg
Eff. Stiffness, K_e=	10400928	N/m
Base Shear, V_b=	5208	kN

Table D.42: Calculation of Height of Contraflexure

Level	**Hi (m)**	**mi (kg)**	**mi.Hi (kg.m)**	$F_{i(relative)}$ **(kN)**	$V_{i(relative)}$ **(kN)**	$M_{i(relative)}$ **(kN.m)**	$V_{i,frame}$ **(kN)**	$V_{i,wall}$ **(kN)**	$M_{i,wall}$ **(kN.m)**	$M_{i,frame}$ **(kN.m)**
15	45	388230	17470350	0.113	0.113	0.000	0.400	-0.287	0.000	0.000
14	42	433640	18212880	0.118	0.232	0.340	0.400	-0.168	-0.860	1.200
13	39	433640	16911960	0.110	0.341	1.035	0.400	-0.059	-1.365	2.400
12	36	433640	15611040	0.101	0.443	2.059	0.400	0.043	-1.541	3.600
11	33	433640	14310120	0.093	0.536	3.387	0.400	0.136	-1.413	4.800
10	30	433640	13009200	0.084	0.620	4.994	0.400	0.220	-1.006	6.000
9	27	433640	11708280	0.076	0.696	6.854	0.400	0.296	-0.346	7.200
8	24	433640	10407360	0.068	0.764	8.942	0.400	0.364	0.542	8.400
7	21	433640	9106440	0.059	0.823	11.233	0.400	0.423	1.633	9.600
6	18	433640	7805520	0.051	0.873	13.701	0.400	0.473	2.901	10.800
5	15	433640	6504600	0.042	0.916	16.321	0.400	0.516	4.321	12.000
4	12	433640	5203680	0.034	0.949	19.068	0.400	0.549	5.868	13.200
3	9	433640	3902760	0.025	0.975	21.916	0.400	0.575	7.516	14.400
2	6	433640	2601840	0.017	0.992	24.840	0.400	0.592	9.240	15.600
1	3	433640	1300920	0.008	1.000	27.814	0.400	0.600	11.014	16.800
0	0	0	0	0.000	1.000	30.814	0.400	0.600	12.814	18.000
Sum		6459190	154066950	1.000						

Table D.43: DBD Displacement Profile

Level	**Height Hi (m)**	**Mass mi (kg)**	**Yield Displ. (m)**	**Design Displ. (m)**	**mi.**Δ_{di}^2 **(kg.**m^2**)**	**mi.**Δ_{di} **(kg.m)**	**mi.**Δ_{di}**.Hi (kg.**m^2**)**
15	45	348522	0.358	0.740	191013	258016	11610702
14	42	382926	0.328	0.685	179846	262426	11021895
13	39	382926	0.299	0.630	152139	241367	9413314
12	36	382926	0.269	0.575	126749	220308	7931088
11	33	382926	0.240	0.520	103676	199249	6575215
10	30	382926	0.210	0.465	82919	178190	5345697
9	27	382926	0.181	0.410	64478	157131	4242533
8	24	382926	0.151	0.355	48361	136083	3266001
7	21	382926	0.122	0.301	34672	115225	2419720
6	18	382926	0.095	0.248	23497	94857	1707419
5	15	382926	0.069	0.197	14801	75283	1129251
4	12	382926	0.046	0.148	8428	56810	681716
3	9	382926	0.027	0.104	4124	39740	357660
2	6	382926	0.013	0.064	1552	24379	146273
1	3	382926	0.003	0.029	318	11031	33092
0	0	0	0.000	0.000	0	0	0
Sum		5709480			1036572	2070094	65881577

Table D.44: Displacement Comparison (in mm)

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD Yield	DBD Design
15	49.5	38.8	357.6	740.3
14	45.9	35.9	328.1	685.3
13	42.1	33.1	298.6	630.3
12	38.2	30.1	269.1	575.3
11	34.2	27	239.7	520.3
10	30.1	23.9	210.2	465.3
9	26	20.8	180.7	410.3
8	21.9	17.6	151.3	355.4
7	17.9	14.5	122.3	300.9
6	14	11.4	94.6	247.7
5	10.4	8.6	69.0	196.6
4	7.1	5.9	46.3	148.4
3	4.3	3.7	27.2	103.8
2	2.1	1.8	12.6	63.7
1	0.6	0.5	3.3	28.8
0	0.0	0.0	0.0	0.0

Table D.45: Drift Comparison

Storeys	IS 1893 Static	IS 1893 Dynamic	DBD - Yield	DBD - Design
15	0.001222	0.00096	0.00983	0.01833
14	0.001257	0.000988	0.00983	0.01833
13	0.001295	0.001017	0.00983	0.01833
12	0.001331	0.001043	0.00983	0.01833
11	0.001359	0.001063	0.00983	0.01833
10	0.001373	0.001074	0.00983	0.01833
9	0.001368	0.001072	0.00982	0.01832
8	0.001341	0.001055	0.00965	0.01816
7	0.001288	0.00102	0.00923	0.01773
6	0.001204	0.000963	0.00853	0.01704
5	0.001088	0.00088	0.00758	0.01608
4	0.000934	0.000766	0.00635	0.01486
3	0.000739	0.000616	0.00487	0.01337
2	0.000499	0.000423	0.00311	0.01162
1	0.000206	0.000179	0.00110	0.00960
0	0	0	0	0

Table D.46: Lateral Forces Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	479	523	591
14	524	494	616
13	452	350	572
12	385	245	528
11	324	185	484
10	267	163	440
9	217	160	396
8	171	161	352
7	131	163	308
6	96	167	264
5	67	171	220
4	43	162	176
3	24	131	132
2	11	82	88
1	3	30	44
0	0	0	0

Table D.47: Storey Shears Comparison (in kN)

Storey	IS 1893 Static	IS 1893 Dynamic	DBD
15	479	523	591
14	1003	1017	1206
13	1456	1367	1778
12	1841	1612	2306
11	2164	1797	2789
10	2432	1961	3229
9	2648	2121	3625
8	2820	2282	3977
7	2951	2445	4285
6	3047	2612	4548
5	3114	2783	4768
4	3157	2945	4944
3	3181	3076	5076
2	3191	3158	5164
1	3194	3188	5208
0	3194	3188	5208

Table D.48: Moment Distribution (in kN.m)

Storey	**DBD - Frame**	**DBD - Wall**	**DBD - Total**
15	0	0	0
14	6250	-4478	1772
13	12500	-7109	5390
12	18749	-8025	10724
11	24999	-7358	17641
10	31249	-5239	26010
9	37499	-1801	35697
8	43748	2824	46572
7	49998	8504	58502
6	56248	15108	71356
5	62498	22504	85002
4	68747	30559	99307
3	74997	39142	114139
2	81247	48121	129368
1	87497	57364	144860
0	93746	66739	160485

Appendix E

List of Paper(s) Communicated/Accepted

- Mehboob H. Jindani, Sharad P. Purohit, Jahanvi M. Suthar, **“Displacement Based Seismic Design of Wall-Frame Building**, Structural Engineering Convention 2014, 9th Biennial Event, IIT Delhi, December 22-24, 2014. **(Abstract Accepted)**