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Earthquake Resistant Design of Low-Rise Open Ground Storey Framed Building

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Abstract: Building an open ground floor is considered vertically irregular buildings to IS 1893: 2002 requires a dynamic analysis considering the strength and rigidity of infill walls. IS 1893: 2002 also allows the equivalent static analysis (ESA) of CGO buildings ignoring the strength and rigidity of infill walls, provided a multiplication factor of 2.5 is applied to the design forces (moments bending and shear forces) in the columns and beams of a floor on the ground. The objective of this study is to examine the rationality of this approach. A framed existing RC building (G + 3) open floor land located in seismic zone V is analyzed for two different cases: (a) given the filling strength and stiffness and (b) without taking into account the filling strength and rigidity (frame). The infill weight (and associated masses) has been modeled in both cases by applying the static dead load. Non-integral filler walls subjected to lateral load behave like diagonal struts. Thus, a filling wall can be modeled as a "compression only equivalent leg in the building model. Rigid joints connect the beams and columns but pin joints connecting the spacers equivalent to the beam-column joints. Infill stiffness was modeled using a diagonal approach according to Smith and Carter (1969). The analysis results show that a factor of 2.5 is too high to be multiplied to the beam and column forces of the ground storey of low-rise open ground storey buildings. This study conclude that the problem of open ground storey buildings cannot be identified properly through elastic analysis as the stiffness of open ground storey building and a similar bare-frame building are almost same. Nonlinear analysis reveals that open ground storey building fails through a ground storey mechanism at a comparatively low base shear and displacement and the mode of failure is found to be brittle. Linear and nonlinear analyses show that support condition influences the response considerably and can be an important parameter to decide the force amplification factor.

Keywords: Infill walls, Diagonal Strut, Open Ground Storey, Equivalent Static Analysis, Response Spectrum Analysis, Pushover Analysis, Low Rise Building, ETABS 2015.

I. INTRODUCTION

A. Overview

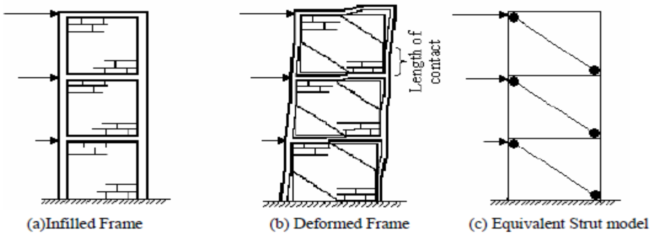
Because of population growth in recent years the car parking space past for residential apartments in populated cities is a major concern. Hence the tendency has been to use the upstairs floor of the building itself for parking. These types of buildings (Fig.1) does not have to fill masonry walls in ground floor, but in filled in all upper floors are called Open Ground Storey (CGO) buildings. They are also known as "open the first storey of the building" (when the numbering of floors begins with one of the ground floor itself), "piles" or "buildings on stilts." The design in such cases will generally be conservative in the case of fully infilled framed building. But things will be different for an OGS framed building. OGS building is slightly stiffer than the bare frame, has larger drift (especially in the ground storey), and fails due to soft storey-mechanism at the ground floor as shown in Fig.2. Therefore, it may be un-conservative to ignore strength and stiffness of infill wall while designing OGS buildings. Non-linear dynamic (NDA) analysis is considered to be the most accurate but at the same time it is most rigorous among all methods. Hence for the present study Equivalent static analysis (ESA), Response spectrum analysis (RSA) and Pushover analysis (PA) is considered for the comparative study as shown in Fig.3.

Fig. 1. Typical example of OGS building.

Fig.2.General mode of failure in OGS buildings.

To carry out these analyses a typical building model with two different cases and support conditions are considered.

- Considering infill strength and stiffness
- Without considering infill strength and stiffness



(a)Infilled Frame (b) Deformed Frame (c) Equivalent Strut model

Fig. 3. Behaviour of in filled frames (ref. Asokan 2006).

B. Objective

Based on the literature review presented in Chapter 2, the salient objectives of the present study have been identified as follows:

- To study the effect of infill strength and stiffness in the seismic analysis of OGS buildings.
- To check the applicability of the multiplication factor of 2.5 as given in the Indian Standard IS 1893:2002 for design of low rise open ground storey building.
- To assess the effect of support condition on the seismic behaviour of OGS buildings.

C. Scope of the Study

Open ground storey (OGS) buildings are commonly constructed in populated countries like India since they provide much needed parking space in an urban environment. Failures observed in past earthquakes show that the collapse of such buildings is predominantly due to the formation of soft-storey mechanism in the ground storey columns. This study deals with two different types of support conditions commonly used in analysis and design i.e., fixed and pinned end support condition. All other types of support conditions are not considered in this project. Soil-structure interaction is ignored for the present study.

- Number of storey and number of bays in two orthogonal horizontal directions may have a great effect on the lateral load resisting behaviour of OGS buildings. However, the conclusions drawn in the present study are based on a case study of a low-rise building (4 storeys).
- It is assumed in the present study that infill panels are having no window and door openings while modelling the infill walls.
- Point plastic flexural hinges only is considered for modelling the frame elements as the building is designed as per current design codes of practices and it is assumed no shear failure will precede the flexural failure.
- In the present study building models are analyzed only using linear static, dynamic analysis and nonlinear static (pushover) analysis. Although nonlinear dynamic analysis is superior to other analysis procedures, it is kept outside the scope of the present study due to time limitation.

D. Methodology

The methodology worked out to achieve the above-mentioned objectives is as follows:

- Review the existing literature and Indian design code provision for designing the OGS building
- Select an existing building model for the case study.
- Model the selected building with and without considering infill strength/ stiffness. Models need to consider two types of end support conditions as mentioned above.
- Linear analysis of the selected building model and a comparative study on the results obtained from the analyses.
- Nonlinear analysis of the selected building model and a comparative study on the results obtained from the analyses.
- Observations of results and discussions.

II. REVIEW OF LITERATURE

A. Overview

A state of the art literature review is carried out as part of the present study. This chapter presents a brief summary of the literature review. The literature review is divided into two parts. The first part deals with the seismic behaviour of the open ground storey buildings whereas the second part of this chapter discusses about the previous work carried out on the linear and nonlinear modelling of infill walls.

Seismic Behavior of Construction Open Floor: Lateral loading of the frame and the filling wall remain intact initially. As the side load increases the filling wall separates the frame surrounding the (voltage) corner unloaded, but in the compression wedge filler walls are still intact. The length over which the fill wall and the frame are intact is called the length of contact. The load transfer occurs through a perfectly diagonal which acts as a compression strut. Modelling of Moment-Curvature in RC Sections using the modified model of Mander stress-strain curves for concrete (Panagiotakos and Fardis, 2001) and Indian Standard IS curve 456 (2000) stress-strain for reinforcing steel for a specific containment steel moment curvature relationships can be generated for the beams and columns (for different levels of axial load). The assumptions and the procedure used to produce the moment-curvature curves are described below.

Assumptions:

- The strain is linear over the height of the section ("plane sections remain plane).
- The tensile strength of concrete is ignored.
- Spalling the concrete off to a strain of 0.0035.
- iv. The initial tangent modulus of concrete, E. c is adopted from IS 456 (2000), as5000ckf
- For determining the position of the neutral axis, convergence is assumed to be achieved within an acceptable tolerance of 1%.

Algorithm for Generating Moment-Curvature Relation:

- Assign a value to the extreme concrete compressive fibre strain (normally starting with a very small value).

- Assume a value of neutral axis depth measured from the extreme concrete compressive fibre.
- Calculate the strain and the corresponding stress at the centroid of each longitudinal reinforcement bar.
- Determine the stress distribution in the concrete compressive region based on the Modified Mander stress-strain model for given volumetric ratio of confining steel. The resultant concrete compressive force is then obtained by numerical integration of the stress over the entire compressive region.

Elastic Analysis Approach: The modelling of infill wall as an equivalent diagonal compression member was introduced by Holmes (1961). The thickness of the equivalent diagonal strut was recommended as the thickness of the infill wall itself, and the width recommended as one-third of the diagonal length of infill panel. The width of the strut using Airy's stress function was found to vary from d/4 to d/11 depending on the panel proportions. Later, a number of tests conducted by Smith (1966) proved that the equivalent strut width (w) is a function of relative stiffness (λh) of the frame and infill wall, strength of equivalent corner crushing mode of failure (R_c) and instantaneous diagonal compression in the infill wall (R_i).

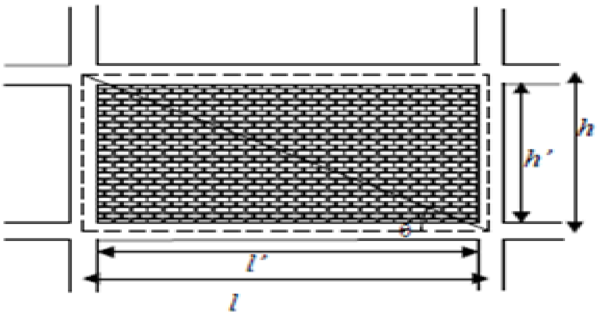


Fig.4. A typical panel of the in filled frame.

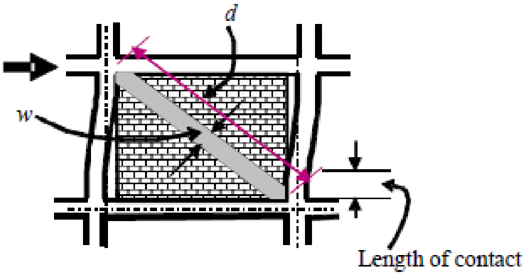


Fig. 5. Behaviour of typical panel subjected to lateral load.

In 1969, Smith and Carter combined all the previous works (Smith 1962, 1966) and developed an analysis approach based on the equivalent strut concept to predict the width and strength of an in filled frame. This approach of modelling the struts is based on the initial stiffness of the infill wall. Fig 4 and 5 shows how the infill panels behave when it is designed as equivalent diagonal strut when subjected to lateral load. Smith and Carter (1969) expressed the parameter, λh, as follows.

$$\lambda h = \sqrt[4]{\frac{E_s t \sin 2\theta}{4 E_c I_c h'}} \qquad (1)$$

Where

E_s = elastic modulus of the equivalent strut

E_c = elastic modulus of the column in the bounding frame

I_c = moment of inertia of the column

h' = clear height of infill wall (Fig. 2.1)

h = height of column between centrelines of beams

t = thickness of infill wall

θ = slope of the infill wall diagonal to the horizontal

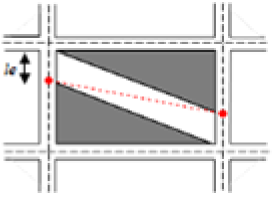


Fig.6. Position of eccentric strut (A1-chaar, 2002).

where $l_e = \frac{w}{\cos\theta}$ and w is calculated using eq(1).

The infill wall thickness was 120 mm and he from his study concluded that the EA approach is simple in calculation as shown in Fig.6. A higher strut width gives higher stiffness and hence, higher base shear in a building. Since the EA approach gives higher strut width, it is conservative in estimating the base shear. For estimating the lateral drift of a building, since the UL approach gives lower stiffness of a strut, it is more conservative as shown in Fig.7.

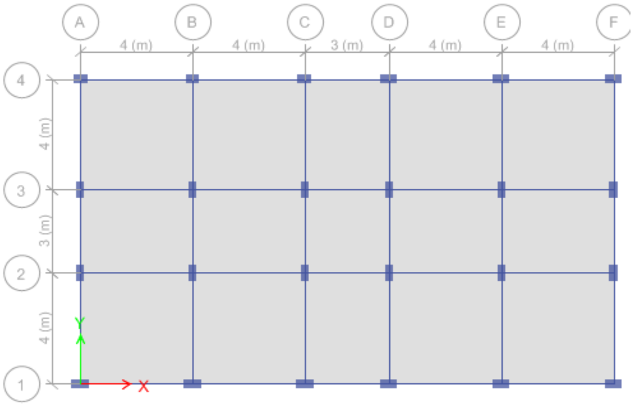


Fig.7.Planned view of G+3 Building.

B. Summary

This Chapter discusses briefly the previous work done on the area of seismic behaviour of open ground storey RC buildings and modelling of infill walls as equivalent diagonal strut. From these published work it can be concluded that that even though the brick masonry in infilled frame are intended to be non-structural, they can have considerable influence on the lateral response of the building as shown in Fig.8.

Multiplication factor to increase the design forces of ground storey columns and beams of OGS buildings is a function of storey numbers. IS 1893:2002 (Part-1) proposal for multiplication factor of 2.5 may not be appropriate for low rise building. The four different approaches namely (a) Elastic analysis approach (b) Ultimate load approach (c) Plastic analysis approach and (d) approach based on Finite element analysis, to model the infill walls is described in detail in this chapter.

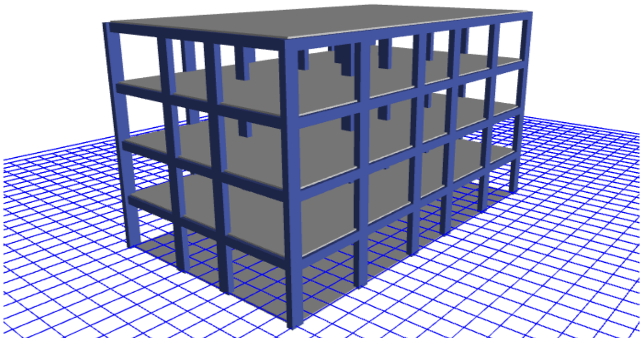


Fig.8.3D Rendering View of G+3 Building

III. STRUCTURAL MODELLING

It is very important to develop a computational model on which linear/non-linear, static/dynamic analysis is performed. The first part of this chapter presents a summary of various parameters defining the computational models, the basic assumptions and the geometry of the selected building considered for this study. Accurate modelling of the nonlinear properties of various structural elements is very important in nonlinear analysis. In the present study, frame elements were modelled with inelastic flexural hinges using point plastic model. A detailed description on the nonlinear modelling of RC frames is presented in this chapter. Infill walls are modelled as equivalent diagonal strut elements. The last part of the chapter deals with the computational model of the equivalent strut including modelling nonlinearity.

A. Building Description

An existing OGS framed building located at Guwahati, India (Seismic Zone V) is selected for the present study. The building is fairly symmetric in plan and in elevation.

No. of Floors of Building – G+3
Slab Thickness – 150 m
Each Floor Height – 3 m
Total Height of the Building – 12 m
External Wall Thick – 230 mm
Internal Thickness – 120 mm
For Live Load – 2 kN/m
Column Sizes – 300 x 600 mm
Beam Sizes – 300 x 450 mm

The cross sections of the structural members (columns 300 mm×600 mm and beams 300 x 450 mm) are equal in all frames and all stories. Storey masses to 295 and 237 tonnes in the bottom storyes and at the roof level, respectively. The design base shear was equal to 0.15 times the total weight.

For Calculation of Dead Load:

Self- weight- 1 kn/Sq.m
Floor load -2 kN/Sq.m
External wall Thickness – 230mm
For Density of Brick Wall = 20 kN/ m^2
= 20 x 0.23 x 3
= 13.8 kN/m^3
Internal wall Thickness – 120mm
For Density of Brick Wall = 20 kN/ m^2
= 20 x 0.12 x 3
= 7.2 kN/m^3
For Considering of Floor Load -1.8 kN/m^2
Live Load – 2 kN/ m

0.3.1 With the increased adoption of the code, a number of comments were received on provisions on live load values adopted for different occupancies as shown in Fig.9. Simultaneously, live load surveys have been carried out in America and Canada to arrive at realistic live loads based on actual determination of loading (movable and immovable) in different occupancies. Keeping this in view and other developments in the field of wind engineering; the Sectional Committee responsible for the preparation of the standard has decided to prepare the second revision in the following five parts:

- Part 1 Dead loads
- Part 2 Imposed loads
- Part 3 Wind loads
- Part 4 Snow loads
- Part 5 Special loads and loads combinations

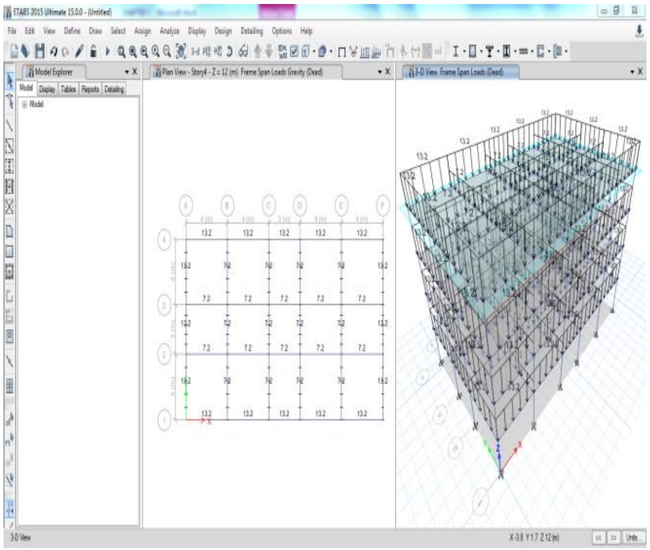
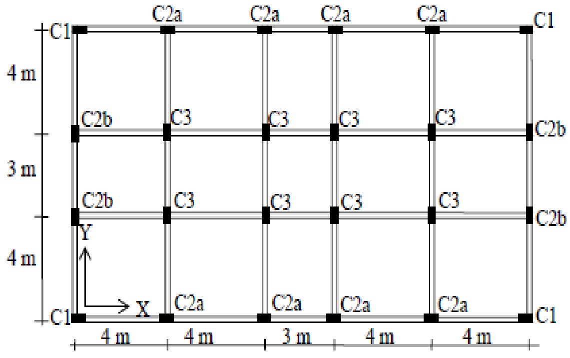


Fig.9.Dead Load on G+3 Building.

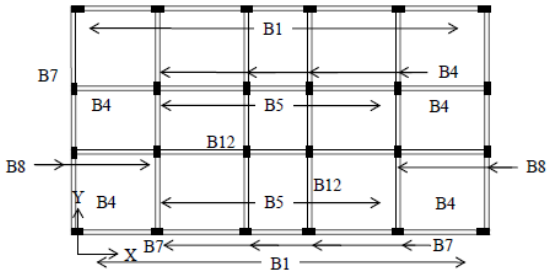
B. Scope

1.1 This code (Part I) covers unit weight/mass of nationals, and parts or components Ina building that apply to the determination of dead loads In the desIln of buildmgs. 1.1. J The unit weight/mass of maternal thatarc likely to be stored in a building are also specifiedfor the purpose of load calculations along with angles of maternal canon as appropriate as shown in Figs.10 and 11.



(a) Column Locations

Fig.10. presents typical floor plans showing different column and beam locations.



(b) Beam Locations

Fig.11. Typical floor plan of the selected building.

C. Equivalent Static Analysis

This is a linear static analysis. This approach defines a way to represent the effect of the earthquake ground motion when forces of the series are to act on a building, across a seismic design response spectrum. This method assumes that the building meets in its fundamental mode. The applicability of this method is extended in many building codes by applying factors to account for the rise buildings with higher modes, and for low torque levels. To take account of effects due to a "yield" of the structure, many codes apply modification factors that reduce design forces. In the equivalent static method, the lateral force equivalent to the design basis earthquake is applied statically. Lateral forces equivalent to the level of each stage are applied to the design "center of mass places. It is located to the eccentricity of the design of the "center of rigidity (or stiffness)" calculated.

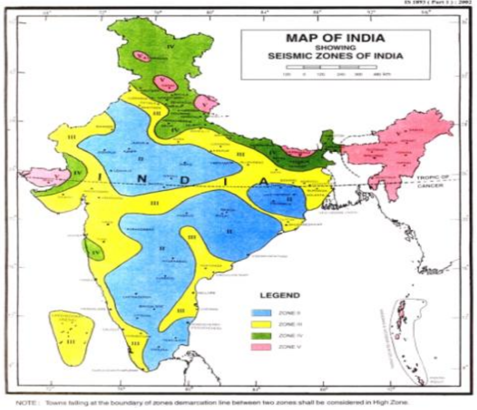


Fig.12.

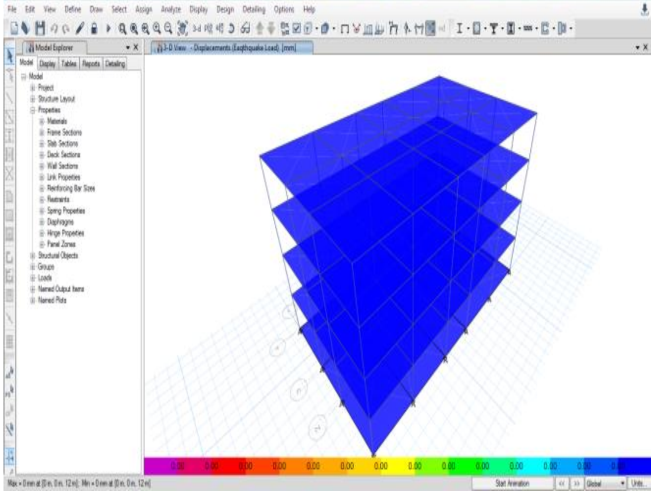


Fig.13.

Material Properties: M-20 grade of concrete and Fe-500 grade of reinforcing steel are used for all the frame models used in this study. Elastic material properties of these materials are taken as per Indian Standard IS 456: 2000. The short-term modulus of elasticity (E_c) of concrete is taken as:

$$E_c = 5000\sqrt{f_{ck}}MPa \tag{2}$$

f_{ck} is the characteristic compressive strength of concrete cube in MPa at 28-day (20 MPa in this case). For the steel rebar, yield stress (f_y) and modulus of elasticity (E_s) is taken as per IS 456:2000. The material chosen for the infill walls was masonry whose compressive strength (f_m’) from the literature was found out to be 1.5 MPa and the modulus of elasticity was stated as: E_m = 350 to 800 MPa for table moulded brick = 2500 to 5000 MPa for wire cut brick According to FEMA 356:2000 elasticity of modulus of brick is taken as E_m = 750 f_m’. For the present study the modulus of elasticity of the masonry is taken as given in literature by Asokan (2006).

Modelling Infill Walls: Infill walls are two dimensional elements that can be modelled with orthotropic plate element for linear analysis of buildings with infill wall. But the nonlinear modelling of a two dimensional plate element is not understood well. Therefore infill wall has to bethe structural effect of slabs due to their in-plane stiffness is taken into account by assigning ‘diaphragm’ action at each floor level. The mass/weight contribution of slab is modelled separately on the supporting beams modelled with a one-dimensional line element for nonlinear analysis of the buildings. Same building model with infill walls modelled as one-dimensional line element is used in the present study for both linear and nonlinear analyses. Infill walls are modelled here as equivalent diagonal strut elements. Section 3.5 explains the modelling of infill was as diagonal strut in detail. Fig. 14 presents a three-dimensional computer model of building without and with considering infill stiffness.

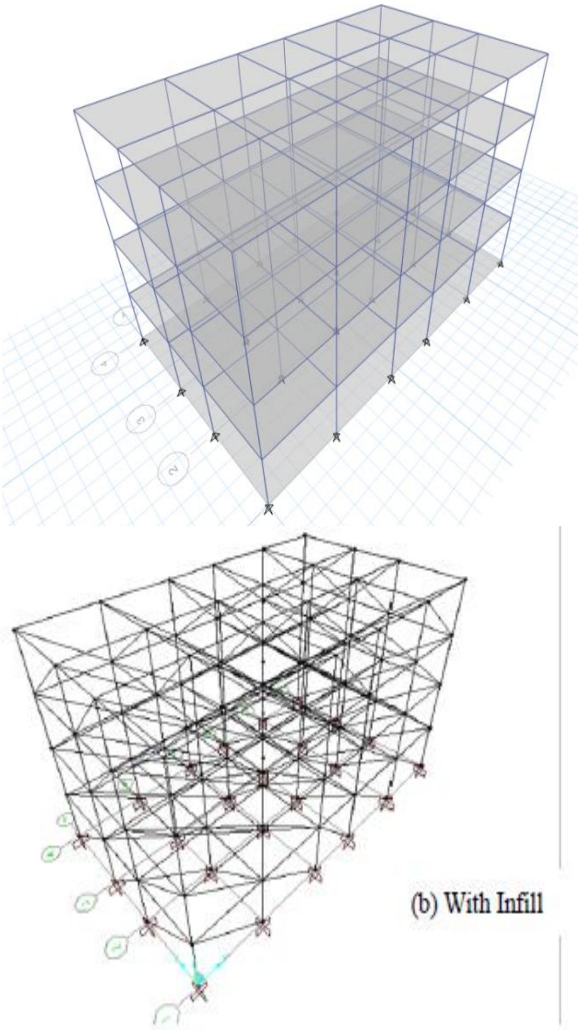
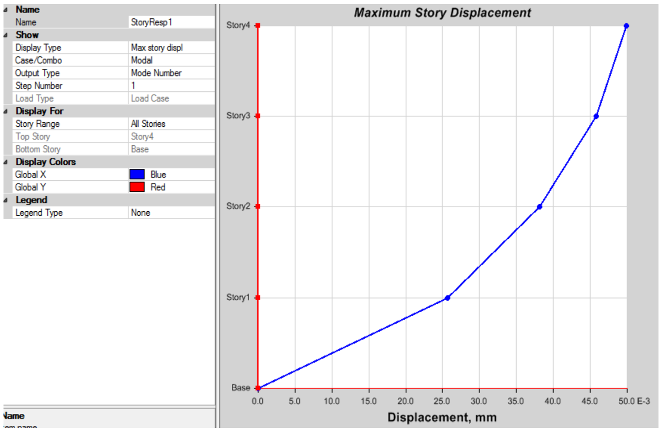


Fig.14. 3D Computer model of building without and with considering infill stiffness respectively.

Moment-Curvature Relationship: Moment-curvature relation is a basic tool in the calculation of deformations in flexural members. It has an important role to play in predicting the behaviour of reinforced concrete (RC) members under flexure. In nonlinear analysis, it is used to consider secondary effects and to model plastic hinge behaviour.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Case/Combo: Modal
Output Type: Mode Number
Step Number: 1
Load Type: Load Case
Display For
Story Range: All Stories
Top Story: Story4
Bottom Story: Base
Display Colors
Global X: 🟦 Blue
Global Y: 🟥 Red
Legend
Legend Type: None

Fig.15.

D. Summary

The first part of the chapter presents the geometry, section sizes, reinforcement details and other important information about the selected OGS building. The next part of this chapter describes the issues related to computational modelling of a framed building followed by a detailed procedure on nonlinear frame element modelling with point plastic flexural hinges. This includes generating uncoupled moment-rotation parameters for beams and coupled axial load-biaxial moment-rotation interaction parameters for columns. The last part of the chapter discusses the modelling of infill wall as equivalent diagonal strut element as per Smith and Carter (1969). Also, modelling of nonlinear axial hinge properties for equivalent strut is explained here based on elastic analysis approach.

IV. RESULTS FROM LINEAR ANALYSIS

Seismic analysis is a subset of structural analysis and is the calculation of the response of the building structure to earthquake and is a relevant part of structural design where earthquakes are prevalent. The seismic analysis of a structure involves evaluation of the earthquake forces acting at various level of the structure during an earthquake and the effect of such forces on the behaviour of the overall structure. The analysis may be static or dynamic in approach as per the code provisions.

A. Response Spectrum Analysis

The equations of motion associated with the response of a structure to ground motion are given by:

$$\ddot{u}(t)_n + 2\zeta_n \omega_n \dot{u}(t)_n + \omega_n^2 u(t)_n = p_{ni}\,\ddot{u}(t)_g \qquad (2)$$

Where *ppnnnn*the Mode Participation Factor are defined by modal participation factor of mode I of vibration is the amount by which mode k contributes to the overall vibration of the structure under horizontal and vertical earthquake ground motions as shown in Fig.16. For a specified ground motion*uü*(*tt*)*gg*, damping value and assuming*ppnnnn*. It is possible to solve above equation at various values of ω and plot a curve of maximum peak response (*ωω*)*MMMM*. For this acceleration input, the curve is defined as Displacement

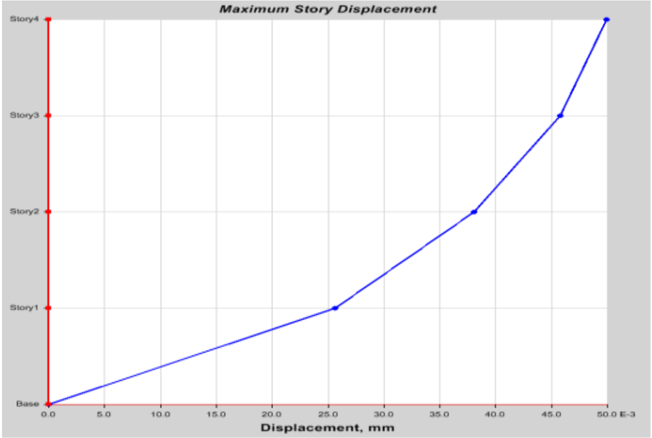


Fig.16. Story Response - Maximum Story Displacement.

B. Summary

This chapter starts with a detailed description of equivalent static analysis procedure and response spectrum analysis procedure as per Indian Standard IS 1893 (Part -1): 2002 followed by the analysis results of selected OGS buildings obtained by these two methods of analyses. It is observed from the results presented here that analysis of the model without considering infill strength and stiffness gives a conservative estimation for all beam and column elements in a low-rise open ground storey building. This is true for equivalent static analysis as well as response spectrum analysis. Therefore, amplification factor of 2.5 as recommended in Indian Standard IS 1893 (Part -1): 2002 need not be multiplied to the beam forces even when infill stiffness is not modelled in analysis. This conclusion based on linear analysis needs to be validated by nonlinear analysis.

TABLE I: Modal Direction Factors

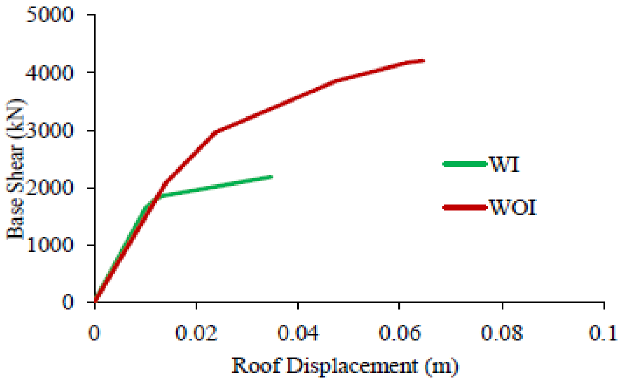
Case	Mode	Period sec	UX	UY	UZ	RZ
Modal	1	0.54	1	0	0	0
Modal	2	0.528	0	1	0	0
Modal	3	0.461	0	0	0	1
Modal	4	0.148	1	0	0	0
Modal	5	0.145	0	1	0	0
Modal	6	0.127	0	0	0	1
Modal	7	0.075	1	0	0	0
Modal	8	0.073	0	1	0	0
Modal	9	0.064	0	0	0	1
Modal	10	0.049	1	0	0	0
Modal	11	0.048	0	1	0	0
Modal	12	0.042	0	0	0	1

V. RESULTS FROM NON-LINEAR ANALYSIS

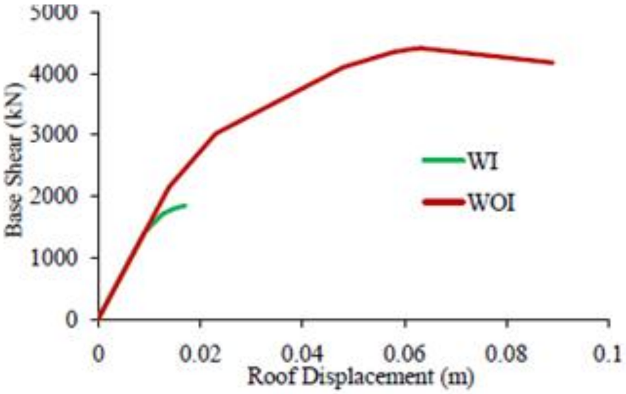
It is found from the linear (static and dynamic) analyses that the amplification factor of 2.5 as recommended in Indian Standard IS 1893 (Part -1): 2002 for designing open ground storey beams and columns are too conservative for low-rise OGS buildings. An effort has been made to verify this conclusion from nonlinear analysis. Pushover Analysis is selected as it is the simplest among the different nonlinear analysis procedures. First half of this chapter presents a detailed description on Pushover Analysis and its procedure. Later half of this chapter presents the results obtained from the pushover analyses of selected open ground storey building for both pinned and fixed end condition. Nonlinear analysis requires modelling of all load resisting elements with material nonlinearity. Modelling nonlinearity for frame elements and infill walls is discussed in Chapter 3.

A. Results From Pushover Analysis

Pushover analysis is carried out for both of the two building models. First pushover analysis is done for the gravity loads (DL+0.25LL) incrementally under load control. The lateral pushover analysis (PUSH-X and PUSH-Y) is followed after the gravity pushover, under displacement control. The building is pushed in lateral directions until the formation of collapse mechanism. The capacity curve (base shear versus roof displacement) is obtained in X- and Y-directions and presented in Figs. 17(a) and 17(b).



(a) X-direction Push



(b) Y-direction Push

Fig.17. Pushover curves for pinned-end building.

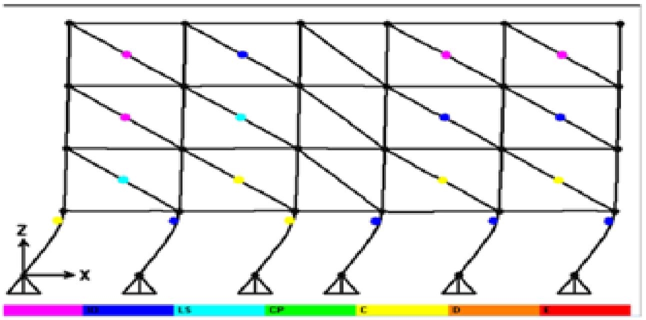


Fig.18. Distribution of plastic hinges for WI Building model.

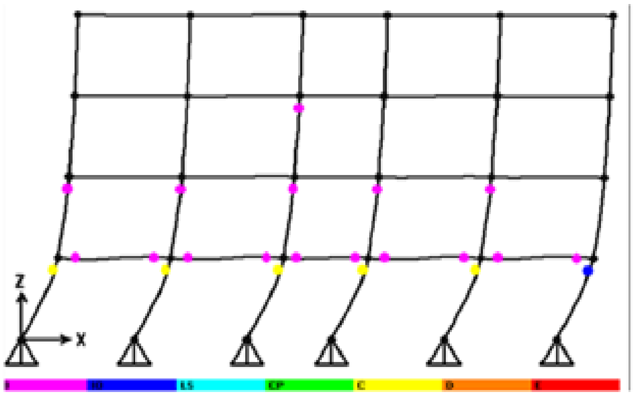


Fig.19. Distribution of plastic hinges for WOI Building model.

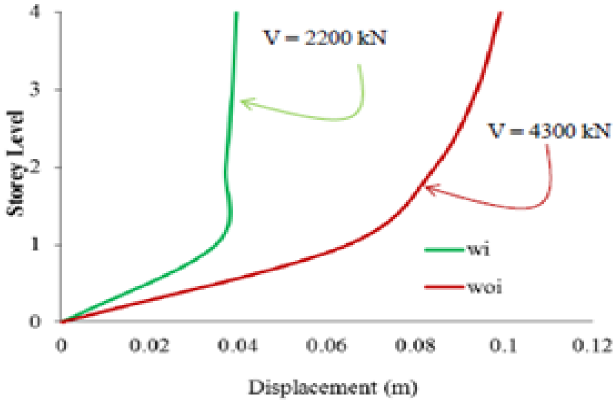


Fig.20. Storey displacement at collapse for pinned end case (Push X).

Figs. 18 and 20 show the results of the building modelled with fixed-end support condition. The pushover curves presented in these figures indicates similar results. WOI model has higher base shear capacity compared to WI model. Obviously in case of fixed end condition the maximum base shear capacity (around 6900kN in X direction) is much higher compared to that of pinned-end building model (4300kN in X direction).

B. Summary

Details of Pushover analysis procedure has been presented in this chapter. Pushover analysis results of the selected building models are discussed. The main conclusion that can be drawn from the pushover analysis results presented here is estimated elastic force demand in the frame elements of OGS building do not change much by ignoring the infill stiffness. But one can wrongly estimate a higher inelastic base shear and displacement capacity of an OGS building by ignoring infill stiffness. The analysis shows that OGS building can have a brittle mode of failure when the infill stiffness is correctly modelled.

VI. SUMMARY AND CONCLUSIONS

Open ground storey buildings are considered as vertically irregular buildings as per IS 1893: 2002 that requires dynamic analysis considering strength and stiffness of the infill walls. IS 1893: 2002 also permits Equivalent Static Analysis (ESA) of OGS buildings ignoring strength and stiffness of the infill walls, provided a multiplication factor of 2.5 is applied on the design forces (bending moments and shear forces) in the ground storey columns and beams. The objective of the present study is to review the rationality of this approach. An existing RC framed building (G+3) with open ground storey located in Seismic Zone-V is analyzed for two different cases: (a) considering infill strength and stiffness and (b) without considering infill strength and stiffness (bare frame). Infill weights (and associated masses) were modelled in both the cases through applying static dead load. Non-integral infill walls subjected to lateral load behave like diagonal struts. Thus an infill wall can be modelled as an equivalent 'compression only' strut in the building model. Rigid joints connect the beams and columns, but pin joints connect the equivalent struts to the beam-to-column junctions. Infill stiffness was modelled using a diagonal strut approach as per Smith and Carter (1969).

A. Conclusions

Followings are the salient conclusions obtained from the present study:

- IS code gives a value of 2.5 to be multiplied to the ground storey beam and column forces when a building has to be designed as open ground storey building or stilt building. The ratio of IR values for columns and DCR values of beams for both the support conditions and building models were found out using ESA and RSA and both the analyses supports that a factor of 2.5 is too high to be multiplied to the beam and column forces of the ground storey. This is particularly true for low-rise OGS buildings.
- Problem of OGS buildings cannot be identified properly through elastic analysis as the stiffness of OGS building and Bare-frame building are almost same.
- Nonlinear analysis reveals that OGS building fails through a ground storey mechanism at a comparatively low base shear and displacement. And the mode of failure is found to be brittle.
- Both elastic and inelastic analyses show that the beams forces at the ground storey reduce drastically for the presence of infill stiffness in the adjacent storey. And design force amplification factor need not be applied to ground storey beams.
- The linear (static/dynamic) analyses show that Column forces at the ground storey increases for the presence of infill wall in the upper storeys. But design force amplification factor found to be much lesser than 2.5.

B. Scope for Future Work

- The proposed results need to be validated by further case studies. Building models considered in this study are of low height and therefore influence of period-shift is negligible. For high-rise buildings shift-in-period can be an additional parameter what is not accounted in the present study.
- Another field of wide research could be the design of the infill walls considering the door and the window openings which has not been considered in this research work.
- It is found in the present study that the multiplication factor of 2.5 as given in IS 1893:2002 is not justified through elastic force demand. However this factor may be required to achieve a ductile mode of failure and to avoid localized storey mechanism. This can be studied elaborately.

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