Evaluation of seismic response of a building with soft story

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Abstract: Open ground story buildings have become a very common feature in multistory constructions in urban India to facilitate the parking requirements. Even though such buildings were found to be vulnerable to earthquake shaking during past earthquakes, their construction is still carried out widely. Such buildings exhibit stiffness irregularity due to absence of infills in the open ground story. This sudden reduction in stiffness causes higher stresses to be concentrated at the ground story columns leading to its failure.

This study mainly aims at studying the effect of introducing a soft story in a building. For this three different models of G+15 RC building are being modeled and analyzed in ETABS software using response spectrum method. The stiffness contribution of the infill walls is being considered in the analysis by modeling them as equivalent diagonal struts pinned at both its end. The building is considered to be located on a medium (Type II) soil profile. The behavior of soft storied building is compared with a fully infilled frame building in terms of seismic responses such as modal time period, story stiffness, lateral displacement and story drifts. Also various column forces such as axial, shear, bending moment and torsional moment of the open first story of soft storied building were compared to the forces of first story columns of fully infilled frame building. Also the change in seismic responses as we move from zone III to zone V is evaluated. From the above study, it is found that introduction of soft story poses a threat to life during earthquake shaking.

Key words: equivalent diagonal strut, ETABS, fully infilled, masonry, response spectrum analysis, soft story, stiffness, story drifts.

INTRODUCTION

In several countries, including India it is become very common practice to provide open ground story (in which infill walls are absent) in most of the urban multistoried constructions. The upper storeys have brick infilled wall panels. Such buildings in general, are known as soft storey buildings. These constructions are widely carried out to facilitate the increasing need to provide parking space in urban areas as a result of increased population, unavailability and high cost of land in these areas. Usually the soft story exists at ground level but it could be it at any other story level too depending on the purpose for which it is being constructed. The Indian seismic code IS:1893-2002 (Part-1) defines a soft story as one whose lateral stiffness is less than 70% of that in story above or less than 80% of average lateral stiffness of three stories above. The open ground story buildings behave differently as compared to that of bare framed building (without any infill) or fully infilled framed building. A bare frame resists lateral load through frame action whereas a fully infilled frame resists lateral load through truss action due to introduction of infills. In case of open ground story buildings, the presence of infill walls in the upper stories makes them much stiffer than the open ground storeys. Thus during earthquake shaking the upper stories move almost together as a single block and most of the horizontal displacement of the building occurs in soft ground story. Upper stories being stiffer have smaller inter-storey drifts, resulting in large curvatures, shear forces and bending moments to be concentrated in ground storey columns due to reduced lateral stiffness and strength of the ground storey. This leads to formation of story mechanism in the open ground story which ultimately leads to failure of these buildings. Many buildings collapsed during the past earthquakes especially during Bhuj earthquake of 2001 were due to soft story effect.

AIMS AND OBJECTIVES

This study mainly aims at studying the effect of introducing a soft story in a multistory building. The objectives include carrying out the seismic analysis of following three models of G+15 RC building in ETABS software using response spectrum method

(i) **Control model (CM)** - fully infilled frame located in zone III.
(ii) **Model (M1)** - open first story and brick infill walls in upper storeys located in zone III.
(iii) **Model (M2)** -open first story and brick infill walls in upper storeys located in zone V.

Various seismic responses such as modal time period, story stiffness, story drifts, and lateral displacements are computed. The column forces of open ground story are also evaluated. Based on these responses, the behavior of soft storied building is compared with a fully infilled frame building. Also comparison of responses when zone is changed from III to V is done.

LITERATURE REVIEW

Zubair Ahmed, S; et al. (2014) In this research, G+5 RC building is modeled and analyzed in ETABS software for three different cases i.e. model with no infill wall (bare frame), model with bottom storey open and model with steel bracing in the bottom storey. Dynamic analysis carried out using response spectrum method and performance of building evaluated in terms of storey drifts, lateral displacements, lateral forces, storey stiffness, base shear, time period and torsion.

Arlekar, J.N; et al. (1997) Investigated the behaviour of G+3 RC framed structure by using ETABS. Nine different models were analysed. Equivalent static analysis and dynamic analysis using response spectrum method were done. Argued for indiscriminate use of open first storey and suggested alternate measures such as column stiffening, provision of core wall, inclusion of soil flexibility for stiffness balance of open first storey.

Hirde, S; Tepugade, G. (2014) Discussed the performance of a G+20 RC building with soft storey at different level along with at GL using nonlinear static pushover analysis. Found that plastic hinges developed in columns of ground level soft storey which is not acceptable criteria for safe design. Displacement reduces when the soft storey is provided at higher level. Hence models retrofitted with shear walls.

Kaushik, H. B; et al. (2009) In this study, several strengthening schemes were evaluated for improving the performance of open ground storey buildings. Non linear analysis was carried out. Developed a rational method for the calculation of the required increase in strength of open first-story columns. Other strengthening schemes such as providing additional columns, diagonal bracings, and lateral buttresses in the open first story. Code methods increased only lateral strength whereas, some of the alternate schemes studied improved both lateral strength and ductility.

Setia, S; Sharma, V. (2012) Typical six storied RC frame is analyzed and modeled in STAAD-Pro software. Equivalent static analysis performed on five different models. Concluded minimum displacement for corner column is observed in the building in which a shear wall is introduced in X-direction as well as in Z-direction. Buildings with increased column stiffness of ground storey perform well in case of storey shear.

Maaze Md. R; Dyavanal S. S. (2013) They modeled bare frame and soft storey frame considering them as special and ordinary moment resisting frame (SMRF & OMRF) for medium soil profile under zone III using SAP 2000 V15 software. Equivalent static, response spectrum and nonlinear static pushover analysis was carried out for default hinge properties. It was concluded that the performance of buildings having non-ductile moment resisting frames can be improved by adding infill walls and SMRF building models are found to more resistant to earthquake loads as compared to the OMRF building levels.

BUILDING DESCRIPTION

The plan layout of a typical fifteen-story (G+15) RC moment resisting frame as shown in Fig. 1 is considered for the analysis. The building has plan dimensions of 24.5m x 17.5m. The frame is assumed to be of special moment-resisting type (SMRF). The building is intended for residential use. Columns C1 and C2 represent external and internal columns of the building. In the seismic weight calculations, only 25% of the live load is considered. Infill walls are assumed to be made of brick masonry and are modeled as equivalent diagonal struts. The building is founded on medium strength soil. The effect of soil structure interaction is not considered in analysis. The plan has seven and five bays of 3.5m span each in X & Y directions respectively. The other relevant details are as given in the Table-1.

Table -1: Preliminary data

Story height	3.2 m
Depth of foundation	2.0 m
Unit weight of RCC	25 KN/m^2
Unit weight of masonry	18 KN/m^2
Live load intensity on floor	3.0 KN/m^2
Live load intensity on roof	2.0 KN/m^2
Weight of floor finish	1.5 KN/m^2
Water proofing load on roof	2.0 KN/m^2
Thickness of external wall	230 mm
Thickness of internal wall	115 mm
Slab thickness	150 mm
Height of parapet	1.0 m
Seismic Zone	III and V
Importance Factor	1.0 m
Response reduction factor	5
Grade of concrete	M30
Grade of steel	Fe500
Compressive strength of masonry f'm	8.5 N/mm^2
Column sizes: G-12th floor	400x400 mm
13th-15th floor	300x300 mm
Beam sizes	300x450 mm
Damping	5%
SBC of soil	200 KN/m^2

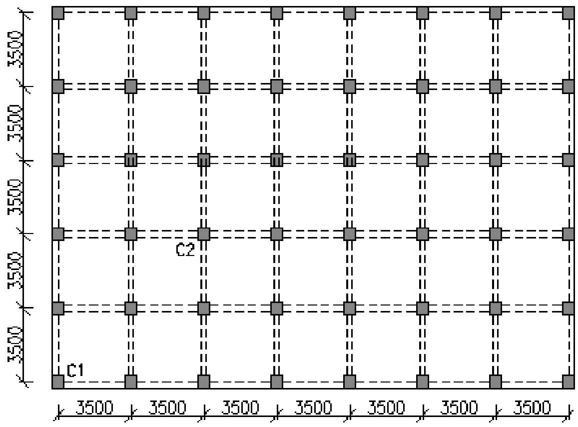

Fig. 1: Plan considered for analysis

METHODOLOGY

The methodology involves studying the provision given for buildings with soft storey in seismic code IS:1893-2002 (Part-1) and also reviewing the existing literature. A rectangular building plan is selected for the study. The building models are analyzed by taking the most severe load combinations as per IS:1893(Part-1)-2002. Three models of the building as stated above are modeled and analyzed in ETABS software using response spectrum method. The elevations of different building models are shown in Fig.2 and Fig.3. Further concluding discussion is carried out on basis of various seismic responses obtained by plotting them graphically.

Structural Modeling

Modeling a building involves the modeling and assemblage of its various load carrying elements. The model must ideally represent the mass distribution, strength and deformability. The beams are modeled as line element with six degrees of freedom at each node and slab as a four nodded membrane element with three degrees of freedom at each node. The infill walls are modeled as equivalent diagonal struts to incorporate the stiffness of infills. The end connections of strut are assumed to be pinned to the confining frame. Floor slabs are modeled as a rigid diaphragm to ensure integral action of all the vertical lateral load-resisting elements. The column to footing connection is considered as fixed.

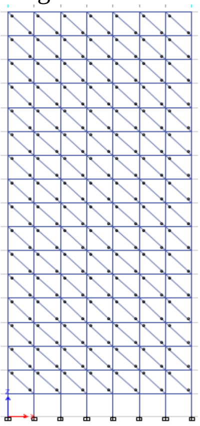

Fig. 2: Control model

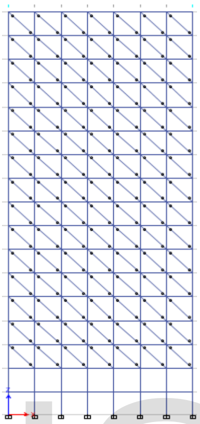

Fig. 3: M1 & M2 model

Modeling of infill walls

Infills are considered as non – structural elements in conventional design practice but they do influence the overall behavior of the structure. Infills increase initial strength and stiffness of RC frame buildings. Research has proved that the infill system behave as a braced frame with the wall forming 'compression struts'. Hence the infills are being modeled as equivalent diagonal struts. This strut is modeled in such as way that it will not contribute for resisting any bending moment but will certainly contribute the stiffness of wall. The material properties and thickness of struts are same as that of masonry wall. To calculate the effective width of strut various empirical formulae are available. In this study, the formula proposed by Mainstone in 1971 is used to calculate the equivalent width of the strut. Fig. 3 depicts representation of infill as equivalent diagonal strut. 'dm' represents diagonal length of the infill, l' is clear span of the infill panel & 'h' the clear height of column. The equivalent strut width, 'Z' depends on a relative flexural stiffness of the infill to that of the column of the confining frame. The relative infill to frame stiffness shall be evaluated by using following equation:

$$\lambda = \left[\frac{Em\ tm\ \sin 2\theta}{4\ Ef\ Ic\ hm}\right]^{\left(\frac{1}{4}\right)} - - - - - - - - - - - - - - - (3.1)$$

$$\theta = tan^{-1}\left(\frac{hm}{lm}\right) - - - - - - - - - - - - - - - - - (3.2)$$

$$Em = 550f'm - - - - - - - - - - - - - - - - - - (3.3)$$

$$Ef = 5000\sqrt{fck} - - - - - - - - - - - - - - - - - (3.4)$$

Hence the equivalent width of the strut as per Mainstone is calculated as follows:

$$Z = 0.175dm(\lambda * hm)^{-0.4} - - - - - - - - - - - - (3.5)$$

Where

Z = Equivalent width of strut

λ = Relative infill to frame stiffness

E_m = Young's modulus of elasticity for masonry (taken as per IS:1905-1987)

E_f = Young's modulus of elasticity of the frame (taken as per IS:456-2000)

I_c = Moment of inertia of column cross-section

θ = angle of inclination of diagonal strut with the horizontal

h_m = effective height of column

t_m = thickness of strut

l_m = effective length of the panel

d_m = diagonal length of infill

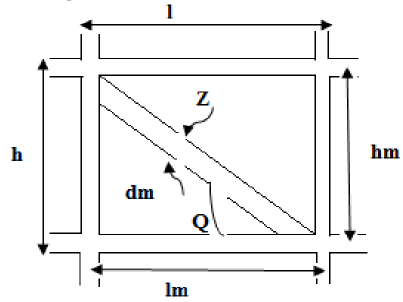

Fig. 4: Equivalent width of strut

Response Spectrum Analysis

The dynamic analysis is carried out using response spectrum method. In this method, the response of a structure during an earthquake is obtained directly from the earthquake response spectrum. This procedure gives an approximate peak response, but this is quite accurate for structural design applications. In this approach, the multiple modes of response of a building to an earthquake are taken into account. For each mode, a response is read from the design spectrum, based on the modal frequency and the modal mass. The responses of different modes are combined to provide an estimate of total response of the structure using modal combination methods such as complete quadratic combination (CQC), square root of sum of squares (SRSS), or absolute sum (ABS) method. Response spectrum method of analysis should be performed using the design spectrum specified or by a site – specific design spectrum, which is specifically prepared for a structure at a particular project site. The same may be used for the design at the discretion of the project authorities.

RESULTS AND DISCUSSIONS

The Dynamic analysis was carried out on G+15 RC multistory building using Response spectrum method in ETABS software. Various seismic responses such as modal time period, story stiffness, maximum displacements, story drifts, story shear and maximum forces for bottom story columns are evaluated and compared. On basis of comparison, the effect of using soft story in a building especially in seismically active areas is highlighted.

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Natural Period

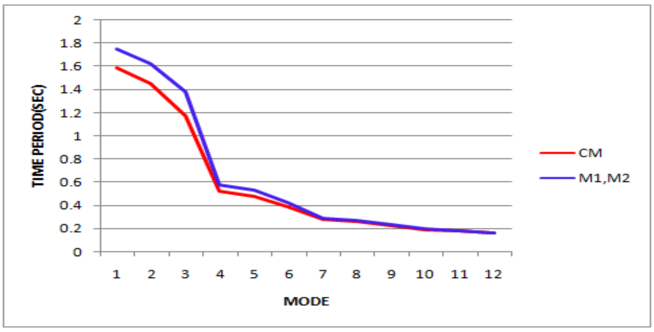

Fig. 5: Modal Time Period

As seen above, the time period for models M1 and M2 is the same since the stiffness of these models is the same irrespective of the zones in which they are located. The time period is inversely proportional to the stiffness of the structure. The time period for models M1 and M2 is found to be more than control model without soft storey. This is because of stiffness reduction in the ground story of models M1 and M2 due to presence of soft story whereas in case of control model the infill walls are present throughout in all the stories thus increasing the stiffness and reducing the time period. Also modeling of infills as equivalent diagonal struts has further reduced the fundamental natural period which is function of mass, stiffness and damping characteristics of the building.

Story stiffness

Story stiffness is defined as the rigidity of the object – the extent to which it resists deformation in response to the applied force. IS 1893:2002 defines soft storey as the one in which the lateral stiffness is less than 70% of that in the storey above it or less than 80% of the average lateral stiffness of three stories above. The building is modeled from founding level with fixed connection and hence level 0 represents the founding level of the building, the level 1 will be plinth level. The variation of lateral stiffness of the building is represented in the figures below:

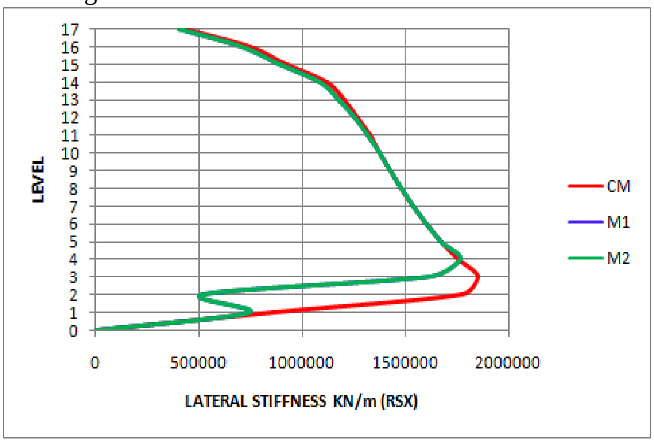

Fig. 6: Story Stiffness (Longitudinal)

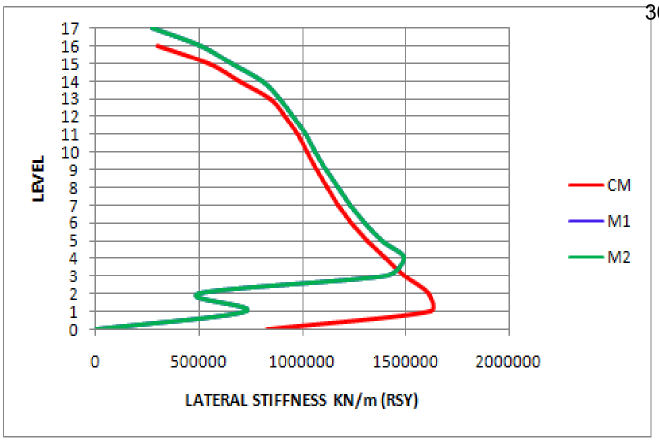

Fig. 7: Story Stiffness (Transverse)

The lateral stiffness of the models M1 and M2 are exactly same. It is observed from the above figures there is sudden change in stiffness for model M1 and M2, when compared to the control model because of the soft storey effect. The stiffness in longitudinal direction is found to be comparatively more than that in the transverse direction for all models. Also the stiffness of the first story is found to be 32.15% and 35.57% respectively of the second story stiffness in longitudinal and transverse directions for models M1 and M2 which is less than 70%. This reduction in stiffness is due to absence of infills in the first story.

Lateral displacement

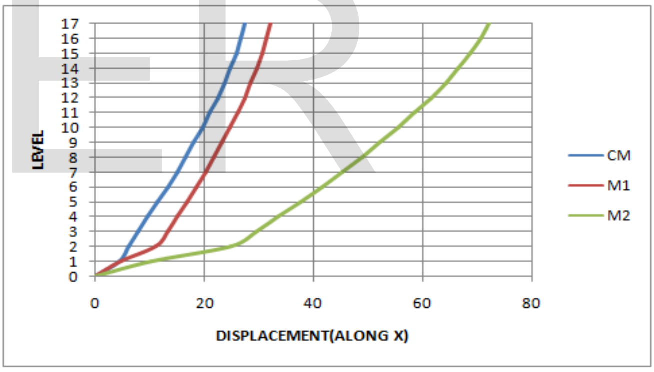

Fig. 8: Longitudinal displacement

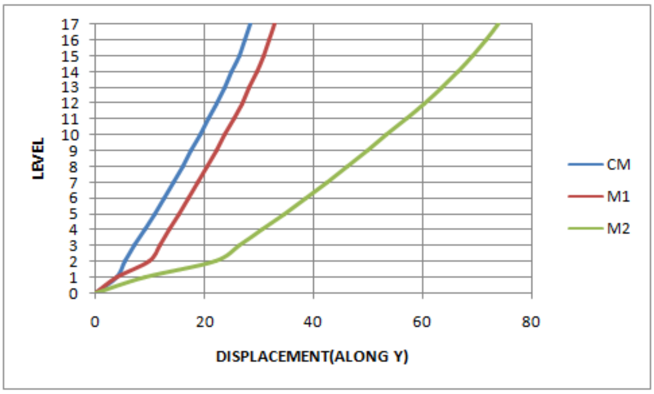

Fig. 9: Transverse displacement

The displacement profile along both principal directions is as shown in the figures above. The abrupt change in the slope of the displacement profile at the first story level indicates stiffness irregularity in first story. However, the displacement profile at all other story levels is a smooth curve due to presence of infill walls in all the stories above. The ductility demand on the columns in the first story is the largest as the forces due to shaking get concentrated in this story due to reduced stiffness of this story. It is observed that the top floor displacement for model M2 is 2.3 times that in model M1 i.e. the displacement increases 2.3 times as we move from zone III to zone V. It is observed that the displacement increases by 15%-17% in model M1 due to presence of soft story as compared to fully infilled frame i.e. control model.

Story drift

It is the displacement of one level relative to the other level above or below. As per IS:1893-2002 (Part-1), the story drift in any story shall not exceed 0.004 times the story height. The results obtained meet this criterion. There is sudden increase in drift at the first floor level in models M1 and M2. This is due to reduced stiffness of first story level. The story drift profile is as shown in the figures below:

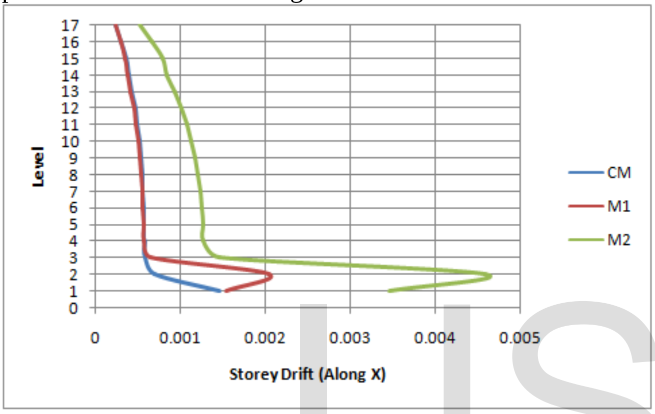

Fig. 10: Story Drift (Longitudinal)

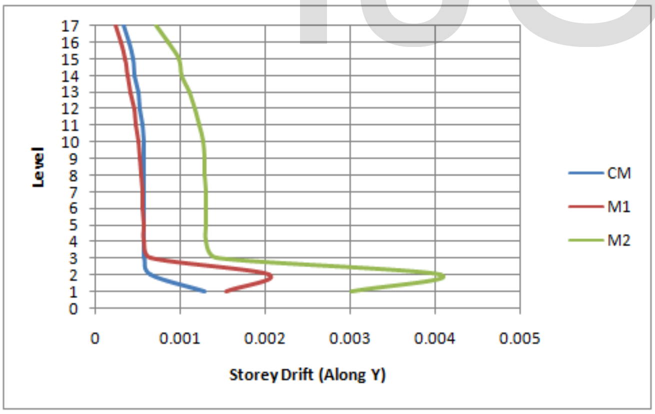

Fig. 11: Story Drift (Transverse)

Column Forces

The observation of column forces at the level of soft storey is crucial. It is expected that the forces for model M1 and M2 will be more as compared to the control model CM. To verify the behavior of building two columns namely C1 and C2 are selected. Column C1 is an outer column located at the periphery of building where as column C2 is an internal column. The variation of forces for all the models are presented below

Axial Forces

The axial forces for external column are found to be more than that for internal column. For external column there is not much variation is observed in models M1 and CM due to change in lateral stiffness. Due to the introduction of soft storey the axial forces are found to be reduced. However, the axial forces in internal column for building with soft storey are around 35 to 45% less than the building without soft storey. There is about 2 to 2.25 increase in axial force as we move from zone III to zone V.

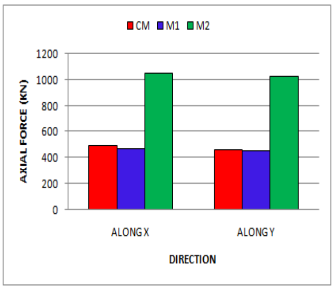

Fig. 12: Axial forces (Ext col)

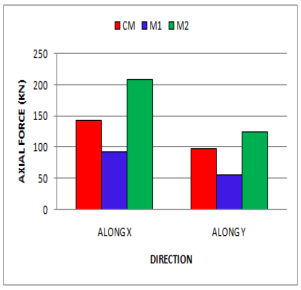

Fig. 13: Axial forces (Int col)

Shear Force

Large increase in shear force was observed for both internal and external columns for building with soft storey. The shear force for internal column was found to be more than that for external column at soft storey level. Increase in shear forces occur due to absence of infill walls in the first story. The shear forces are also found to increase by 2 to 2.25 as we move from zone III to zone V.

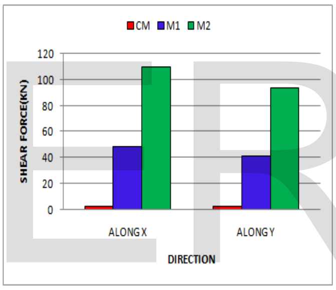

Fig. 14: Shear Force (Ext col)

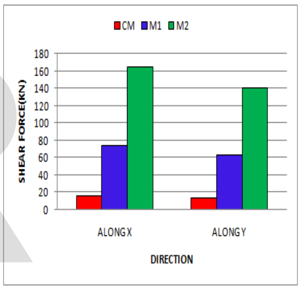

Fig. 15: Shear Force (Int col)

Bending Moment

As can be seen from the figure, the bending moment along both the principle direction increases due to the introduction of soft storey; however the bending moment for internal column is more than that for external column at soft storey level. Due to this the ductility demands of the columns in the first story are very high. There is about 2 to 2.25 increase in bending moment as we move from zone III to zone V.

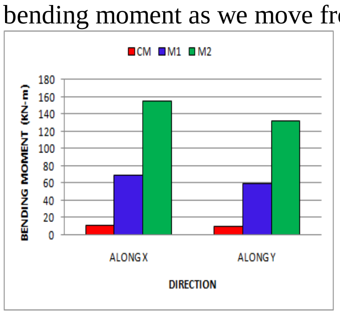

Fig.16: Bending Moment (Ext col)

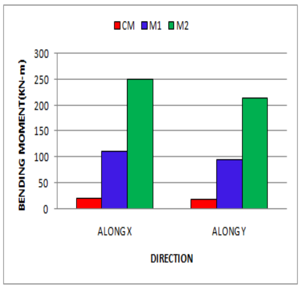

Fig. 17: Bending Moment (Int col)

Torsional Moment

The torsional moment for external column is found to be more than internal column in case fully infilled frame. However, the torsional moments are not considerable at soft storey level for lateral forces.

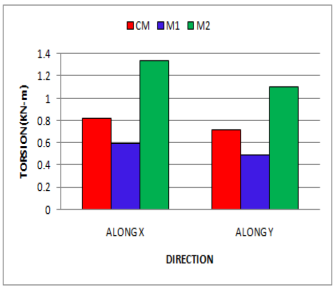

Fig. 17: Torsional Moment (Ext col)

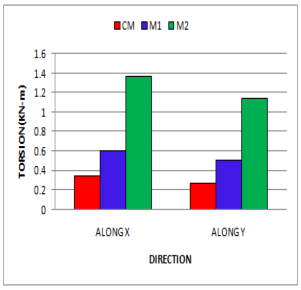

Fig. 18: Torsional Moment (Int col)

CONCLUSIONS

Based on the results obtained from the analysis of all three building models, following conclusions are drawn:

1. It is observed that a very good control over displacement and drift can be achieved by modeling of infill wall using equivalent strut approach.
2. The modal time period of soft storied building is found to be more than that of fully infilled frame building.
3. Large deformation is observed in models M1 and M2 at the location of soft storey at bottom due to reduced stiffness of structure at that level.
4. Presence of soft story at the ground floor causes concentration of forces at the ground story columns causing the columns to be stressed severely, leading to the failure of the building.
5. A soft storey will have 17 to 20% more roof displacement as compared to a building without soft storey.
6. The displacement increases 2.3 times as we move from zone III to zone V.
7. Sudden increase in story drift at the first floor level is observed in models M1 and M2. This is due to reduced stiffness of first story level. In such situations, the columns in the first story should comply with the ductility provisions.
8. The story drift for all models is found to be within permissible limits as per clause 7.11.1 of IS:1893-2002 (Part 1). However the story drift increases as we move from zone III to zone V.
9. The axial forces for the columns along the periphery are found to be more than that for internal column. However, due to the introduction of soft storey the axial forces are found to be reduced. There is huge increase in axial force as we move from zone III to zone V.
10. Large increase in shear force was observed for both internal and external columns for building with soft storey. The shear force for internal column was found to be more than that for external column at soft storey level.
11. The bending moment increases due to the introduction of soft storey; however the bending moment for internal column is more than that for external column at soft storey level.

As observed from the results, the provision of soft storey leads to decrease in axial forces however it will attract very large flexural and shear forces. The torsional effect is found to be negligible. There is around 2 to 2.25 times increase in forces ie axial, shear and moment was observed as we move from moderate (Zone III) to very severe zone (Zone V). Also large deformations demands were observed on the columns of the first soft story. Hence construction of buildings with soft story should be avoided as far as possible in the near future and existing soft story buildings should be strengthened to withstand the strong earthquake shaking. Preventive measures such as column stiffening of soft storey, provision of shear walls and bracings should be undertaken.

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