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Seismic Vulnerability Assessment of Soft Storeyed Structures with Plan Irregularity and Collapse Prevention

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***Abstract*-- Structures with soft storey configuration are most vulnerable under earthquake loading but the risk increases abruptly if the structures are also irregular in plan. In this paper an attempt has been made to assess the seismic vulnerability of such structures by equivalent static force method (ESFM), response spectrum method (RSM) and time history method (THM). Results are obtained and compared with different models and extreme response has been recorded for open ground storey (OGS) building. Due to plan irregularity torsional responses are also involved in structures. To mitigate the soft storey effect and torsional response shear walls are introduced in different locations at OGS, OGS columns are designed 2.5times of the ground storey moment and shear force, OGS columns are replaced by reinforced concrete filled steel tube columns (RCFSTC), and the best solution among these three techniques are presented.**

Key words- Earthquake, Soft storey, Plan irregularity, Shear wall, RC filled steel tubes.

I. INTRODUCTION

With the increment of the population we are facing an unbalanced ratio of land availability to requirement. Irregular structures are mostly in demand because of land optimization, to increase the functional efficiency and aesthetical view. But structural irregularities are not acceptable from stability point of view. Recent earthquakes of Manipur in 2016, Nepal in 2015, Sikim in 2011, Bhuj in 2001, has proved the structural vulnerability during earthquakes. So importance of seismic analysis of the structures, especially irregular structures has been increased heavily. All the structures during earthquakes are proved to be vulnerable but the structures with soft storey configuration i.e, structures with stiffness irregularity in elevation are found to be most vulnerable during earthquake. And the risk factor becomes much more if soft storeyed structures are also irregular in plan, due to addition of torsional response. This deadly combination of stiffness irregularity and torsional response makes the structures too much weak to survive during earthquake. According to IS1893 (Part1) : 2002, any storey which has a lateral stiffness less than 70% of that of the storey immediately above, or less than 80% of the combined stiffness of the three storeys above are called soft storeys. A extreme soft storey is one in which the lateral stiffness is less than 60 % of that in the storey above or less than 70% of the average stiffness of the three storeys above. According to seismic map of India about 60% of land area is reported to be under the threat of moderate to severe seismic hazard. Reinforced concrete frame buildings with open ground storeys, plan irregularity are built in India. Frame bays in the ground floor are not infilled with masonry walls like the upper stories. This effort reduces the stiffness of the lateral load resisting system and torsional response induced due to plan irregularity. As a result progressive collapse becomes unavoidable in a severe earthquake for such buildings due to combination soft storey effect and torsion. Hence it is important to study the responses of such buildings to make such buildings earthquake resistant and prevent their collapse to save the loss of life and property. Murthy (2006) found that open ground storey buildings were highly vulnerable in shear generated during strong earthquakes it was relatively flexible in the ground storey. Setia and Sharma (2012) investigated the behaviour of a building with soft storey in equivalent static analysis method and found lateral displacement was largest in bare frame with soft storey defect. Prakashvel et al. (2012) made an attempt to assess the seismic performance of the soft storey reinforced concrete building by shake table test. During all the shake table tests, strain values were higher at ground storey columns and it was comparatively very low for other storey columns. Goh and Pan (2015) studied the torsional response of non-ductile structures by soft storey by varying the stiffness eccentricity in plan and stiffness magnitude in elevation and found displacement amplification of flexible side was larger than the stiffer side. Ghosh and Debbarma (2015) investigated the deficiency of soft storeyed structure in both response spectrum method and equivalent static force method. They recommended use of shear walls in the soft storey to mitigate it's failure by increasing it's stiffness and controlling it's displacement and drift excellently.

II. DETAILS OF BUILDING ANALYSED

A five storey (G+4) L-shape residential building has been analysed. All the details related to structure are provided here.

A. Seismic Design Data

1. Seismic Zone: V.
2. Zone factor (Z): 0.36.
3. Soil type: Medium soil.
4. Damping ratio: 5%.

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5. Frame Type: Special Moment Resisting Frame.
6. Response reduction factor (R): 5.
7. Importance factor (I): 1.

B. Material Properties

1. Unit weight of concrete: 25 KN/m^3.
2. Unit weight of Infill walls: 21.2068 KN/m^3.
3. Characteristic Strength of concrete: 30 MPa (for structural elements), 25 MPa (for shear wall).
4. Characteristic Strength of steel: 415 MPa.
5. Compressive strength of masonry walls: 4.1 MPa.
7. Modulus of elasticity of masonry walls: 2300 MPa.
8. Characteristic Strength of steel tube: 345 MPa.

C. Structural Elements

1. Beam: 250 mm x 300 mm.
2. Column: 350 mm x 350 mm.
3. Slab thickness: 150 mm.
4. Wall thickness: 250 mm.
5. Parapet height: 1000 mm.
6. Shear wall thickness: 200mm.
7. Single strut width: 1060mm.
8. Steel tube: 550mm x 550mm x 100mm.

D. Loads Considered

The types of load considered during the design are-
1. Dead loads of beams, columns, slab.
2. Wall weight.
3. Live load of 3 KN/m^2 at floors & 1.5 KN/m^2 at roof.
4. Mass source (1DL + 1WL + 0.25LL).

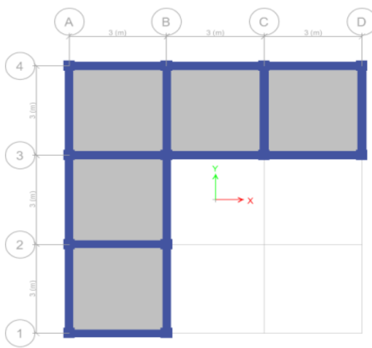

Fig. 1. Plan of the building.

III. MODELLING OF STRUCTURE

The modelling of the structure includes the modelling of structural elements like column, beam, slab, base conditions, joint conditions and shear walls etc, non-structural elements like masonry walls. The models are created and analysed in integrated building design software ETABS2015 version 15.0.0.

A. Structural Elements

Columns are modelled as two nodded rectangular continuous vertical line element and beams are modelled as same but as horizontal elements. The columns are taken to be square to keep the discussion focused only on the soft storey effect, without being distracted by the issues like orientation of columns. The cross sectional areas of the beams are kept smaller than that of columns to justify strong column weak beam theory. Slabs are modelled as four nodded rectangular shell area elements. Base conditions are made fixed by restraining all the degrees of freedom of the each joints of the base. Joint diaphragms in all the joints of the structure are made as fixed to make all the joints act as a single unit containing the nodes of beam column and slabs together on that joint.

B. Masonry Walls

In this paper macro modelling approach has been adopted for modelling the walls which is easy to model and analysis can be done faster and also gives good results. The lengths of the struts are as same as the diagonal length of the wall. Width of the strut has taken as one fourth of the diagonal length of the wall and thickness is as same as the thickness of wall, all other properties of the strut is as same as the properties of masonry wall, Kaushik *et.al* (2007). The struts are modelled as two nodded pinned line elements.

C. Shear Walls

Shear walls have very high in plane stiffness and strength, which can be used to simultaneously resist large horizontal loads and support gravity loads, making them quite advantageous in many structural engineering applications. In this paper M_{25} grade concrete shear walls are modelled as four nodded shell area elements.

D. RC filled Steel Tube Columns (RCFSTC)

Hollow square steel tubes of dimension 550mm x 550mm and thickness of 100mm are used. The hollow tube is filled with same RC column of 350mm x 350mm, which has same grade of concrete (M30) and same distribution of reinforcement of other 350mm x 350mm columns.

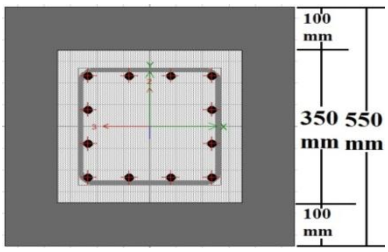

Fig. 2. Cross section of RCFSTC

IV. ANALYSIS METHODS

In this paper all the models are analysed both in linear static method which is known as equivalent static force method and linear dynamic method which is response spectrum method. ESFM analysis and RSM analysis are done and results are compared to study the seismic behaviour of the structures. In modal analyses, mode shapes are generally obtained in normalized form and thus the results of response spectrum method need to be properly scaled. In the present study, the scaling has been done as per IS1893:2002 guideline by equating the base shear obtained from ESFM to that obtained from RSM. In ESFM analysis all the load combinations suggested by IS 1893:2002 has been taken and the combination 1.5(DL±EL) has given the most of the effect. Time history analysis is also done using real earthquake data of Kobe earthquake.

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V. MODELS ANALYSED

Total 8 types of models are analysed in this paper. Name and description of models are given in Table I, and models are shown in Fig.3.

TABLE I. DETAILS OF MODELS

Description of the models	Symbols
Bare frame.	L0
Fully infilled frame with concentric single strut as wall.	L1
OGS but other storeys infilled with concentric single strut as wall.	L2
Same as model L2 but only the corner panels of OGS is infilled with shear wall.	L3
Same as model L2 but only the end panels of the outer sides of OGS are infilled with shear wall.	L4
Same as model L2 but only the end panels of the inner sides of OGS are infilled with shear wall.	L5
Same as model L2 but OGS columns are designed 2.5times of the ground storey moment and shear force, as per IS: 1893(2002).	L6
Same as model L2 but OGS columns are replaced by RCFSTC.	L7

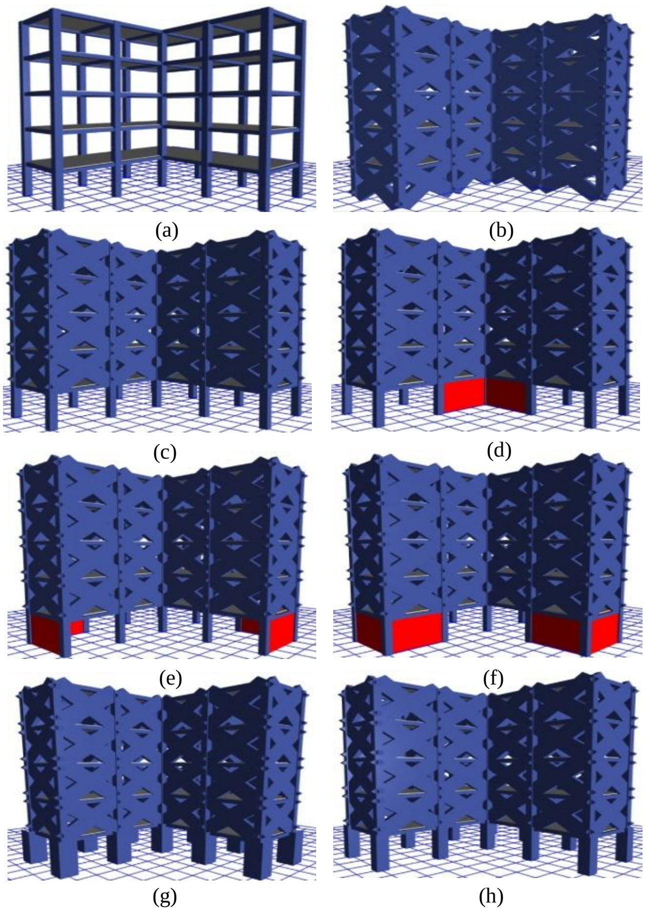


Fig. 3. Images of models. (a) Model L0, (b) Model L1, (c) Model L2, (d) Model L3, (e) Model L4, (f) Model L5, (g) Model L6 and (h) Model L7.

VI. RESULTS AND DISCUSSION

Analysis has been performed and the results obtained for all the models. The OGS models are found most vulnerable in terms of displacement, storey drift, stiffness irregularity. Bending moment and shear force in the columns of OGS model was much more compared to bare frame and fully infilled models. Due to plan irregularity the torsional responses are also recorded in the models. The obtained results are compared and discussed.

A. Base Shear

Base shear due to earthquake force has been obtained in both of the methods ESFM and RSM and balanced by the scale factor as per IS 1893:2002. Base shear for all the models are shown in Fig.4.

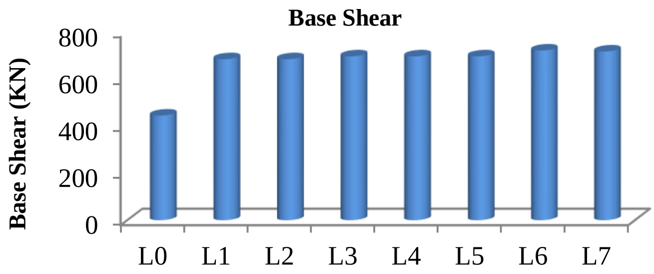
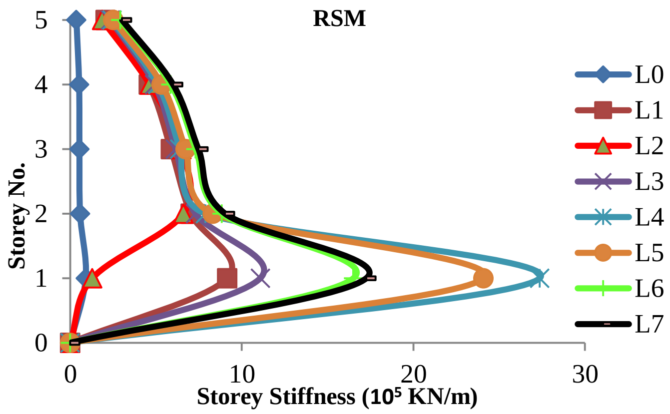


Fig. 4. Base Shear of all the models.

It has been observed that as the base shear is a function of mass and stiffness of the structure, so except bare frame model, in all other models the base shear has been increased due to the stiffness and mass provided by the infilled walls, shear walls and addition of steel tubes. It is noticed that in all three cases like, full infilled models, OGS models, other models in which the ground storey stiffness is modified by shear walls, RCFSTC and increased column section has almost same base shear. It indicates that there is no significant change of base shear on the modification of stiffness at ground storey as the base of the storey is fixed. But little increase in base shears has been recorded, with the increment of mass on those models.

B. Storey Stiffness

The stiffness of a particular storey is the total stiffness provided in the storey by it's column, walls, shear walls etc. The stiffness of the each storey for every model in both methods are shown in the Fig.5.



(a)

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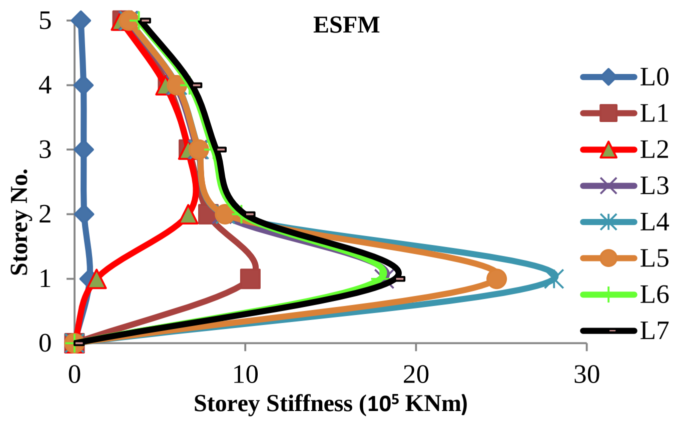


(b)

Fig. 5. Storey Stiffness of all models. (a) by RSM, (b) by ESFM.

From the Fig.5 it can be seen that the nature of stiffness variation along the storey heights in both methods are similar. Model L2 having an OGS at bottom storey shows that the OGS has very less stiffness of the immediate upper storey in both methods. So this model exhibits soft storey effect without any doubt which is most vulnerable during earthquake. To overcome this problem shear walls are introduced on the next models L3, L4 and L5, OGS columns are designed as 2.5 times of OGS moment and shear force in model L6 and RCFSTC are placed in place of regular RC columns of OGS in model L7. The stiffness percentage of the OGS with respect to immediate upper storey is shown in Table II.

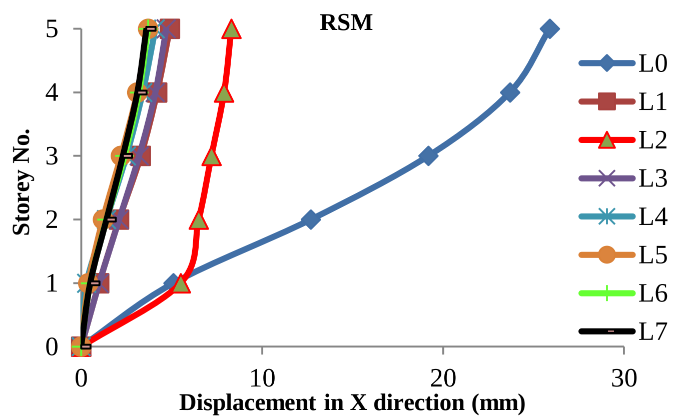
TABLE II. STIFFNESS PERCENTAGE OF OGS

Model	L0	L1	L2	L3	L4	L5	L6	L7
RSM	158.4	130.2	19.4	151.8	347	289.7	186.9	191.3
ESFM	156.6	131.3	19.3	210.0	318	280.5	183.4	187.8

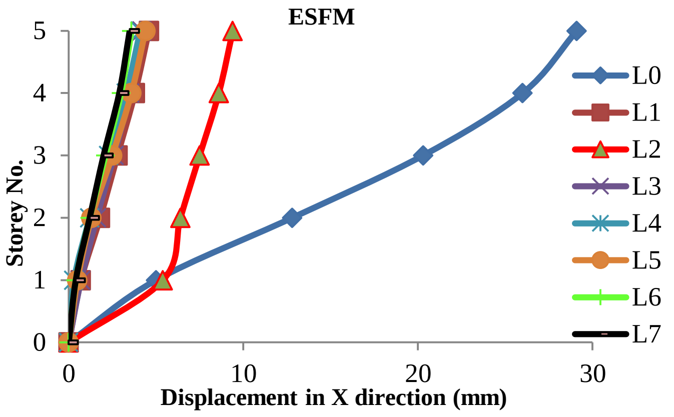
From the Table II. it is clear that all the models except L2 have OGS stiffness more than 70% of the immediate upper storey stiffness. So results show that introduction of shear wall, OGS columns designed as 2.5 times of OGS moment and shear force, RCFSTC in place of regular RC columns of OGS, effectively mitigates the problem of soft storey.

C. Storey Displacements

Storey displacement is calculated in both methods for all the models and results are shown in the Fig.6.



(a)



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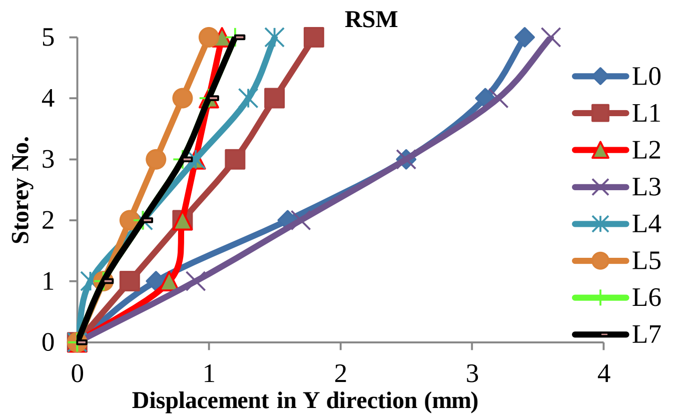

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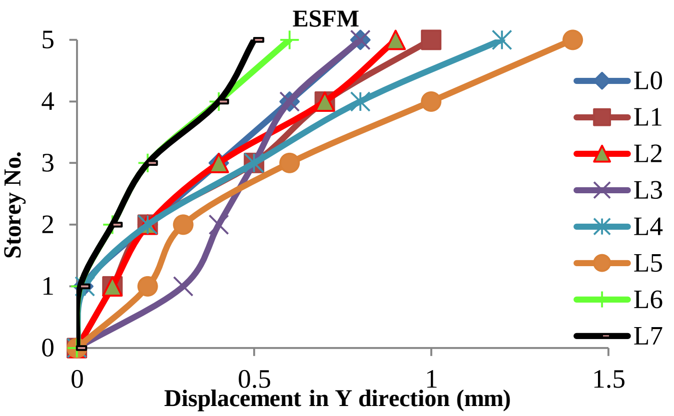

(d)

Fig. 6. Storey displacement. (a) in X direction by RSM, (b) in X direction by ESFM, (c) in Y direction by RSM, (d) in Y direction by ESFM.

Ground storey (GS) displacement in the direction of force i.e, in X direction has been recorded maximum for the model L2 due to lesser stiffness caused by the absence of infill walls in that storey in both methods. The remaining models where OGS is modified by three techniques, show very less storey displacements in comparison with the models L0 and L2. Model L1, which is fully infilled with masonry walls are practically not preferred but the remaining models show very good displacement control, even better than model L1 in both methods. In the transverse direction of force (Y direction) maximum GS displacement has been recorded maximum for model L3 in both methods and GS displacement of model L2

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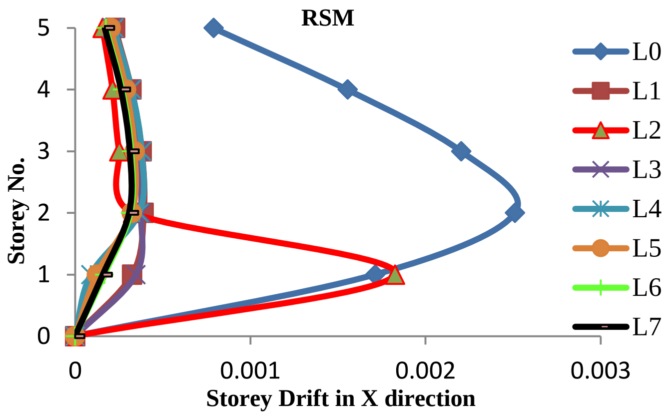
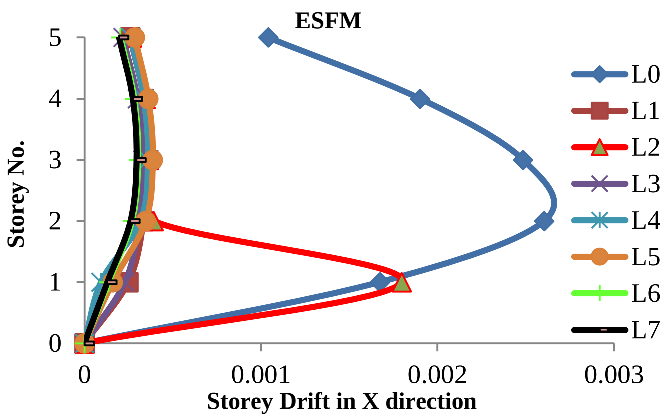
is just little bit less than this. Due to increased flexibility of OGS in model L2, the displacement of GS has become maximum along the direction of force (X direction), as a result displacement in minor direction has reduced by a little margin. Out of all the models model L7, model L6, and model L5 has shown the best displacement control in both methods and in both direction.

D. Storey Drift

Storey drift is the relative displacement between the adjacent floors. It is calculated as difference between the adjacent storey displacements per unit storey height in the direction of force. The results obtained in both RSM and ESFM and shown in the Fig7.



(a)



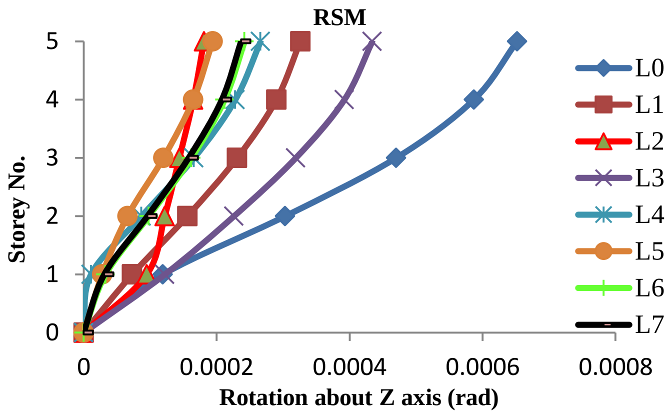
(b)

Fig. 7. Storey drifts. (a) in X direction by RSM, (b) in X direction by ESFM.

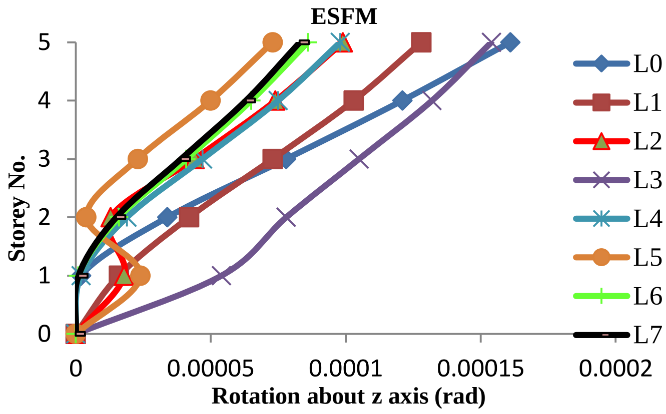
The results in both RSM and ESFM are similar in nature, although their values vary depending on their modelling and analysis method. None of the storey drifts has exceeded the extreme drift criteria of 0.004 as per IS 1893:2002. Model L0 shows maximum storey drift for all the storeys in both methods except ground storey. Ground storey drift is maximum for the L2 in both methods due to soft storey effect. The remaining models show very less inter storey drifts in comparison with the models L0 and L2. Model L1 which is fully infilled with masonry walls are practically not preferred, but the remaining models show very good inter storey drift control even better than model L1 in both methods and the best drift control is recorded for model L7.

E. Torsion

Torsion arises from the eccentricity in a building layout, when the centre of mass of the building does not coincide with it's centre od rigidity. If there is torsion, the building will rotate about it's centre of rigidity due to torsional moment about the centre of structural resistance. As the structure is irregular in plan the torsional response is recorded and storey rotation about vertical (Z) axis shown in Fig.8.



(a)



(b)

Fig. 8. Rotation about Z axis. (a) by RSM, (b) by ESFM.

Results show that rotation takes place in each and every storey and with the increment of the storey height the torsional responses increases. The GS rotation is recorded maximum for model L3, where the shear walls are concentrated on the corner of the building. Due to this this concentration of rigidity in a particular section of the building, sufficient torsional moment is generating about the centre of rigidity under the action of lateral force. The torsional effect of model L2 is lesser than L3, because of the increased flexibility of the OGS of model L2 it does not have sufficient concentrated rigidity on GS to rotate about the centre of rigidity. Out of three models L3, L4, L5, in which the OGS is rectified by shear walls, model L4 shows best rotation control in GS. It indicates that the more spreader construction of shear wall in a building with plan irregularity the less will be the torsional effect. Model L6 and L7 shows very effective and uniform rotation control along the storey height. And unlike the models with shear walls in these models stiffness is not concentrated only on some particular section, rather uniformly distributed over the whole plan. Although the torsional

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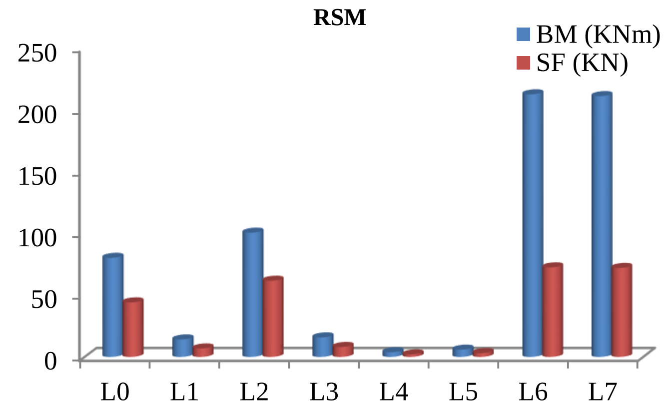
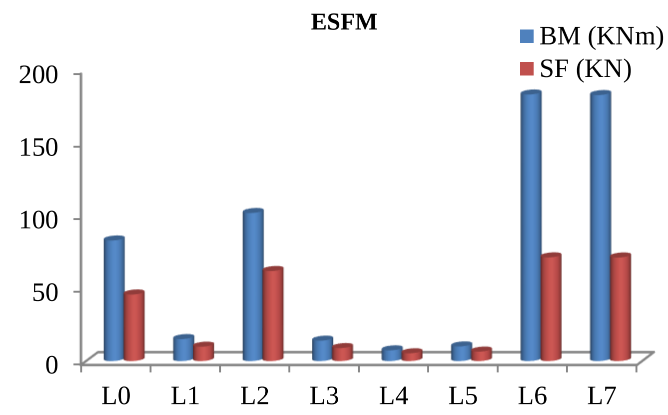
response of OGS model is not the highest among the models but this response little lesser than the highest and it is combined with maximum storey displacement, drift, stiffness deficiency.

F. Ground Storey Column Moments and Shear Forces

When the bare frame model is subjected to earthquake load, mass of each floor acts independently, resulting each floor to drift with respect to adjacent floors. In presence of infill, the relative drift between adjacent floors is restricted causing mass of the upper floors to act together as a single mass. In such a case, the total inertia of the all upper floors causes a significant increase in the horizontal shear at base, as a result in the ground floor columns bending moment (BM) and shear force(SF) increases. The analysis results for all the models are shown in the Fig.9.



(a)



(b)

Fig. 9. OGS column BM and SF (a) by RSM, (b) by ESFM.

From the results it is seen that the bending moment (BM) and shear force (SF) in the ground storey columns in the case of model L2 are greater than model L0 and L1. This is due to the soft storey effect, which is because of discontinuation of walls in the ground storey to make the storey more open in construction. Model L1 which has continuation of walls even in the ground storey shows effective reduction in the ground storey BM and SF, but these models cannot serve the purpose of OGS. Models with shear wall in OGS L3, L4 and L5 exhibit an excellent BM and SF reduction in the ground storey columns which is even better than model L1 in both the methods RSM and ESFM. The BM and SF of ground of OGS columns in the models L6 and L7 has been found maximum due to increased base shear and column section.

G. Time History Results

Time history analysis is done using real earthquake data of Kobe earthquake. The results are shown in Figs.10-13. in terms of base shear, ground storey displacement and torsion for models L2, L3, L6 and L7.

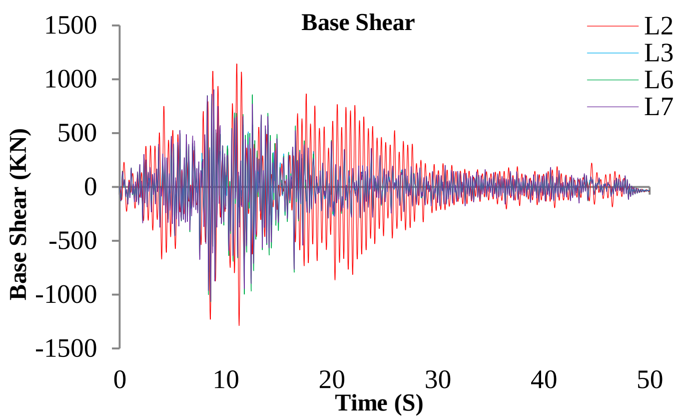


Fig.10. Variation of Base Shear with time.

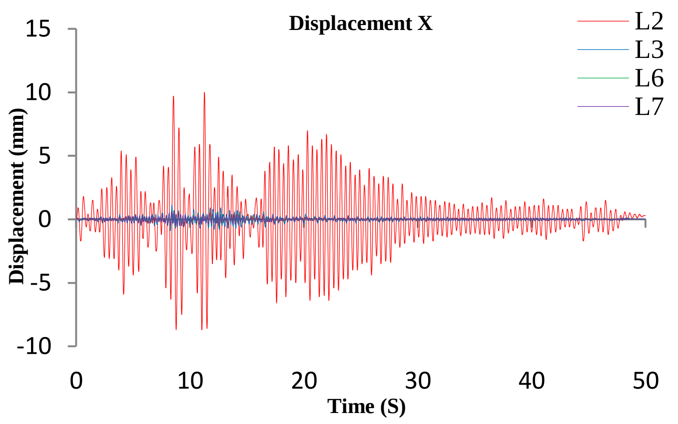


Fig. 11. Variation of Displacement in X direction with time.

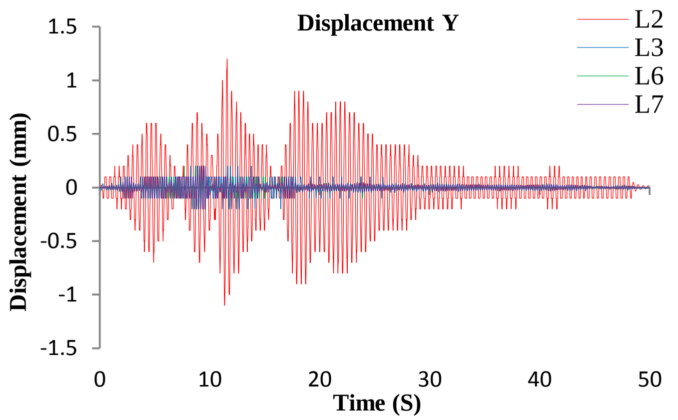


Fig. 12. Variation of Displacement in Y direction with time.

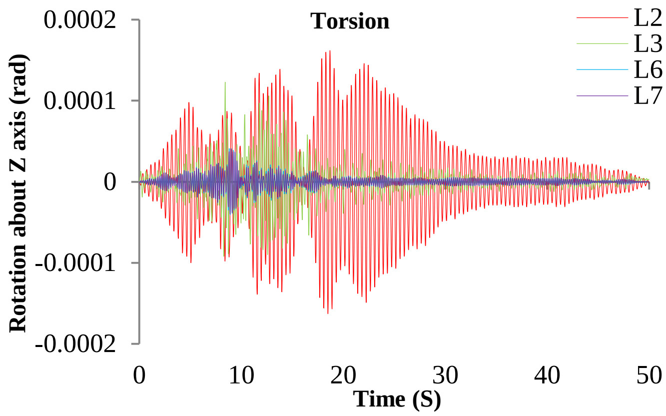


Fig. 13. Variation of Torsional response with time.

Time history results also reveal the vulnerability of soft storeyed structure as the ground storey displacement and torsion of the OGS model L2 is the maximum in the Figs.11-13. The remaining models L3, L6 and L7 have been excellent in displacement and torsion control of open ground storey. And the model L7 where RCFSTC are used in OGS is proved to be most effective among them.

VII. CONCLUSION

In this paper the instability of OGS structures with plan irregularity during earthquake has been studied in two different methods linear static method (ESFM) and linear dynamic method (RSM and THM). The responses of the RSM are lesser than those of the ESFM. The stiffness of OGS model abruptly decreased due to infill discontinuation and is seriously effected under earthquake loading as it's responses are much more than the other models. As the fully infilled models cannot serve the OGS purpose, the OGS models are further modified by introducing RC shear walls in OGS, designing the OGS columns as 2.5 times of storey shear and moments, replacing the OGS columns by RCFSTC. OGS models with all these three techniques behave excellently under earthquake loadings, even better than fully infilled model. The ground storey stiffness of these models using these three techniques are much more than that required to overcome soft storey effect of OGS model, and upper storey stiffness of these models are also gets better. The maximum stiffness is recorded in the case of shear walls, followed by RCFSTC introduction in OGS and then by designing the OGS columns as 2.5 times of storey shear and moments. The storey displacement and torsion control has been found excellent by these three techniques and controlling capacity of these three techniques are also almost same. In the case of torsion, it is seen that the wider construction of shear walls makes the structures lesser prone to torsional effect and uniform distribution of stiffness over the whole plan reduces the torsional response more effectively. But the problem with shear wall models is that shear walls are blocking accesses in OGS, as a result there is reduction in functional efficiency of structures. And the model where OGS columns are designed with 2.5 times of storey shear and moment, has a big increment of column section in OGS. Due to this there is a sudden abrupt change of the RC column section at the junctions of OGS columns and first storey columns, thus the possibility of generation of plastic hinges becomes prominent. Both these problems are effectively solved by using RCFSTC in the OGS, as the model with RCFSTC is not blocking any access in OGS and RC column section is also not changing at the junction. So RCFSTC in OGS has been found as the most effective solution for collapse prevention of soft storeyed structure with plan irregularity during earthquakes. This paper recommends the use of RCFSTC in the place of ordinary RC column at OGS of the multi storeyed building with plan irregularity.

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