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Seismic Performance of 3D RC Asymmetric Framed Buildings using Lightweight Concrete Compared to Normal-Weight Concrete

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Abstract—*Weight of a building is a major factor in performance against seismic loading. Heavy buildings experience higher seismic loads than lighter buildings. In this study, the performance of two ten storied asymmetric (T shaped) RC 3D framed buildings – one with normal-weight concrete and the other with lightweight concrete. Both the normal-weight and the lightweight buildings are analysed and compared using response spectrum analysis, linear time history analysis and static pushover analysis in SAP2000. The lightweight concrete used is argex-expanded clay aggregate concrete. Material properties of the lightweight concrete are collected from one of its importer named GBC INDIA. Both these concretes are kept at same strength level and loading conditions for comparison. The base shear experienced by both the types of buildings are compared with three codes viz., IS 1893:2002, EUROCODE8 2004 and IBC 2006 while the inter-storey drift is compared by using linear time history analysis. Further, static pushover analysis is carried out to observe the difference in performance level in both the buildings. The study results demonstrate that the lightweight concrete building experiences approximately 12-15% (using five different ground motions in both horizontal orthogonal directions) lesser drift than the normal-weight concrete building. Moreover using pushover analysis the lightweight concrete building exhibits a lesser displacement in a greater base shear as compared to the normal-weight concrete building. Also, the base shear acting on the lightweight concrete building for all the three codes is found to be nearly 15% lesser than the normal-weight concrete building. Hence the study reveals the overall better seismic performance of lightweight concrete building as compared to normal-weight concrete building*

1. INTRODUCTION

Conventional Civil engineering structures are designed on the basis of two main criteria that are strength and rigidity. But as the population of the world is increasing monotonically, the balance between demand and supply parameters have somewhat been disturbed. Due to this effect economy is also an important parameter while executing any civil engineering works. Overall taking all these parameters into account, everyone urges for an efficient design and construction practice under which all the conditions are fulfilled.

A good seismic performance analysis and efficient design contributes to the long life of the building [3]. Weight of a building plays a major role in the magnitude of the earthquake load acting on any structure .It implies that a heavier building will experience a more seismic load as compared to a lighter building .Therefore if instead of normal-weight concrete ,a lightweight concrete is used to construct the building, it will have less dead load than the normal concrete as a result of which the building will be lighter and it will experience a less seismic load [1]. At the same time for a safe and efficient design, the structural member sections and the quantity of steel required for a lightweight concrete will be less than that for a normal concrete building. Hence economy without compromising on the stability of a structure can be achieved by using lightweight concrete instead of normal-weight concrete.

1.1 Response spectrum analysis

In order to perform the seismic analysis and design of a structure to be built at a particular location, the actual time history record is required. But, it is not possible to have such records at each and every location. To overcome this difficulty, earthquake response spectrum is the most popular tool in the seismic analysis of structures. The method involves the calculation of only the maximum values of the displacements and member forces in each mode of vibration using smooth design spectra that are the average of several earthquake motions. Different codes have different design spectra with difference in peak value based on which the design base shear is calculated [6, 9]. But sometimes especially in earthquake prone areas the instantaneous response and a very accurate analysis of the response of the previous ground motion becomes very important to design any structure. In this regard, the accurate dynamic analysis cannot be done with response spectrum since it does not provide response in miniature time intervals and this has proved to be one of its disadvantage.

1.2 Linear time history analysis

A linear time history analysis overcomes all the disadvantage of modal response spectrum analysis. In this method of analysis, the considered structure is subjected to some previous ground motions which had occurred earlier and then the response is analysed for each and every fraction of time. Analysis of the structure in such fraction of time intervals reveals the actual behaviour of it when acted upon by such an earthquake. This method requires great computational efforts for calculating the response at such discrete instantaneous times. One advantage of this procedure is that the relative signs of response quantities are preserved in the response histories. This is important when interaction effects are considered in design among stress resultants [6].

1.3 Static pushover analysis

Pushover analysis is an approximate analysis method in which the structure is subjected to monotonically increasing lateral forces with an invariant height-wise distribution until a target displacement is being reached. Pushover analysis consists of a series of sequential and systematic elastic analysis, used in determining a force-displacement curve of the overall structure. In this method, a model of the building generated is subjected to a lateral load. The intensity of the lateral load is slowly increased and the sequence of cracks, yielding, plastic hinge formation and failure of the various structural components are accurately recorded. Pushover analysis provides a significant insight into the weak links in seismic performance of a structure. Series of iterations are usually required during which, the structural deficiencies observed in a particular iteration, are rectified and followed by another. The performance criteria for pushover analysis is generally established as the desired state of the building given a roof-top or spectral displacement amplitude [5].

1.4 Building performance level

The various seismic performance ranges obtained after analysis and design of a building are defined as building performance level. The four building performance levels are Collapse Prevention, Life Safety, Immediate Occupancy and Operational. These levels are discrete points on continuous scale describing the building’s expected performance, or alternatively, how much damage, economic loss, and disruption may occur [2]**.**

1. Operational Performance level: It means the post-earthquake state which is the highest performance level in the building during which the building undergoes a very little and minimum damage.
2. Immediate Occupancy (IO) level: It means the post-earthquake damage state in which only very limited structural damage has occurred. The risk of life threatening injury as a result of structural damage is very low.
3. Life Safety (LS) level: It means the post-earthquake damage state in which significant damage to the structure has occurred, but some margin against partial or total structural collapse remains.
4. Collapse Protection (CP) level: It means the building is on the verge of experiencing partial or total collapse. Substantial damage to the structure has occurred, including significant degradation in the stiffness and strength of the lateral force resisting system, large permanent lateral deformation of the structure.

2. METHODOLOGY

A G+9 asymmetric (having T shaped plan) building was modeled in SAP2000 and was designed accordingly. At first, the building was modeled by using the material properties of normal-weight concrete and then, the same building was modeled using the properties of the lightweight concrete [8].

2.1 Material properties

The material properties of both the types of concrete used in designing the building are shown in Table 1.

Table 1: Material properties used to design the building

Properties	Normal-weight concrete	Lightweight concrete
Concrete type	M30	M30
Rebar	Fe 500, Fe 250	Fe 500, Fe 250
Unit weight, γ (kg/m3)	25	15.11
Characteristic Strength, fck (N/mm2)	30	30
Modulus of Elasticity, E (N/mm2)	27386.14	27386.14
Poisson’s Ratio ,μ	0.15	0.15
Shear stress reduction factor	N.A	0.75

2.2 Section properties

The sectional properties are kept same for both types of concrete building for comparison. The section properties used in both the buildings are shown in Table 2.

Table 2: Dimensions of various members of the considered RC buildings with normal-weight concrete and lightweight concrete

Member	Dimension
Beam	500mm×600mm
Column (Type-1)	600mm×600mm
Column (Type-2)	650mm×650mm
Column (Type-3)	500mm×500mm
Column (Type-4)	550mm×550mm
Column (Type-5)	380mm×380mm
Column (Type-6)	460mm×460mm
Slab (thickness)	125mm
Infill-wall (thickness)	127mm

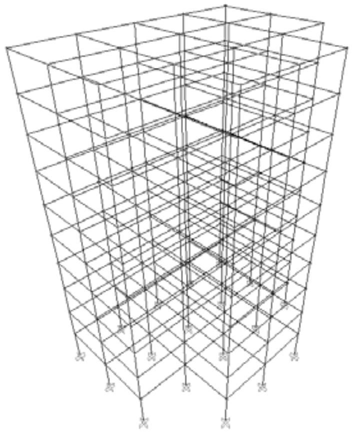


Fig. 1: SAP2000 model (skeletal view) of the sample building.

3. RESULTS AND DISCUSSIONS

3.1 Comparison of modal properties

Modal properties like natural frequencies, mode shapes have significant contribution in dynamics performance of any structure [6]. Significant vibrations are likely to be produced in structures, if the natural frequency range of dominant modes matches with the earthquake frequency content-range [4, 7]. Therefore, it is a great interest to observe the changes in natural frequencies in case of the lightweight concrete building in comparison with the normal-weight building. The frequency, time period and circular frequencies were obtained after analyzing the buildings and compared accordingly in a tabular form for both the types of buildings as shown in Table 2 and Table 3.

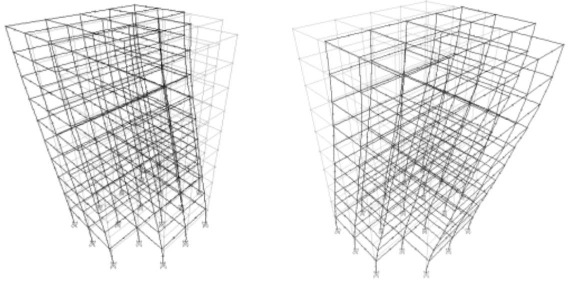
Table 2: Modal parameters for 5 modes in normal-weight concrete building.

Mode No.	Normal-weight Concrete building		
	Time period (sec)	Frequency (Hz)	Circular-freq. (rad/sec)
1	1.457	0.686	4.311
2	1.402	0.713	4.480
3	1.261	0.792	4.978
4	0.524	1.907	11.984
5	0.506	1.976	12.417

Table 3: Modal parameters for 5 modes in lightweight concrete building.

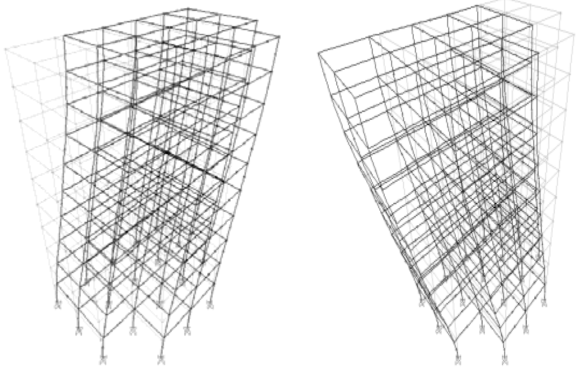
Mode No.	Lightweight Concrete building		
	Time period (sec)	Frequency (Hz)	Circular-freq. (rad/sec)
1	1.396	0.730	4.587
2	1.318	0.758	4.766
3	1.196	0.835	5.252
4	0.493	2.027	12.741
5	0.476	2.100	13.200

A total of five modes were taken for the comparison with their frequencies and time periods. It was observed that both the frequencies were higher for the lightweight concrete building as compared to the normal-weight concrete building and subsequently the time period was less. Further, mode shapes for the first three dominant modes are shown in Figures 2-4.



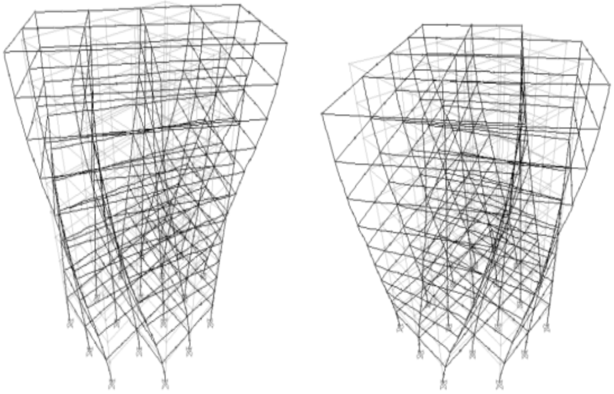
(a) (b)

Fig. 2: 1st mode shape for the considered (a) normal-weight and (b) lightweight building.



(a) (b)

Fig. 3: 2nd mode shape for the considered (a) normal-weight and (b) lightweight building.



(a) (b)

Fig. 4: 3rd mode shape for the considered (a) normal-weight and (b) lightweight building.

3.2 Comparison of base shear force by response spectrum analysis with three different codes

Base shear is the total lateral force at the base of the structure. There are many methods for calculating the lateral force at the base [6]. Different countries adopt different codes for calculating base shear. Here by response spectrum analysis in SAP 2000, the base shear is obtained for three different codes for a medium stiff ground profile. CODE 1 is EUROCODE8 2004, CODE 2 is IS 1893 (PART 1): 2002, CODE 3 is IBC 2006. The above mentioned codes have their own response spectrum function and based on that, the maximum base shear force is obtained. The base shear thus obtained from these three codes are then compared for normal-weight concrete building and lightweight concrete building as shown in Fig. 4 and Fig. 5 for both horizontal orthogonal (x and y) directions respectively.

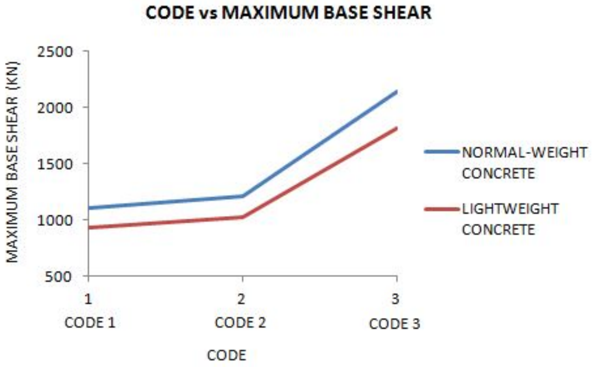


Fig. 4: Maximum Base Shear plot in x- direction

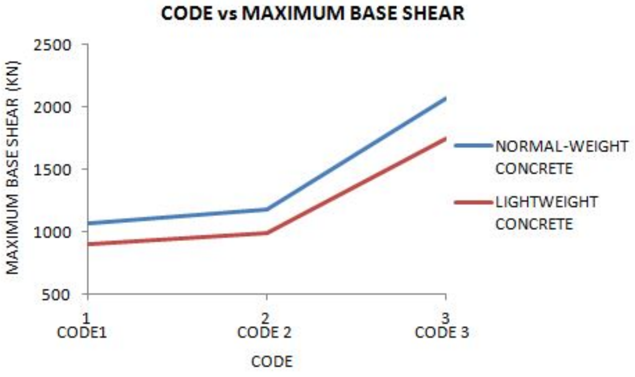


Fig. 5: Maximum Base Shear plot in y- direction

From the above figures it can be inferred that IBC 2006 (CODE 3) gives the highest base shear than IS 1893:2002 (CODE 2) and EUROCODE8 2004 (CODE 1) and CODE 1 gives the lowest value of base shear. As comparing both the types of concrete it is estimated that the lightweight concrete building experiences about 15% lesser base shear in both x and y directions than normal-weight building.

3.3 Comparison of inter-storey drift by linear time history analysis

Time history method is a very accurate seismic method of analysis. The response obtained from linear time history method is very effective in analyzing various parameters important for seismic design. Inter-storey drift is an important parameter with which one can access how much a building is deviating from its natural position under a particular ground motion [6, 9]. The maximum inter-storey drift against five different ground motions are shown in fig. 6 and fig.7 in both x and y directions respectively.

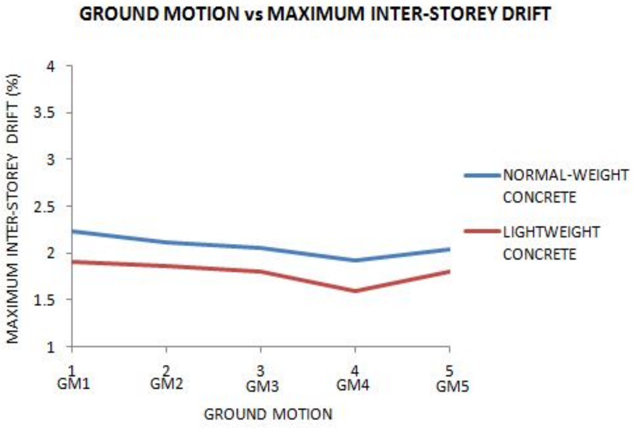


Fig. 6: Maximum Inter-storey drift in x- direction

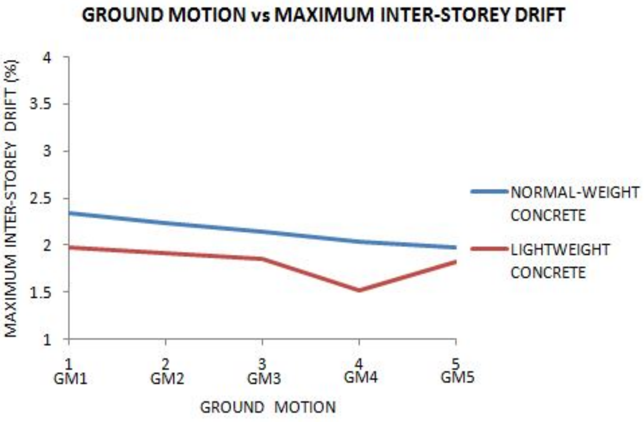


Fig. 7: Maximum Inter-storey drift in y- direction

In fig. 6 and 7, ground motion is abbreviated as GM. GM1 is Kobe earthquake, GM2 is Northridge earthquake, GM3 is El-Centro earthquake, GM4 is N. Palm strings earthquake and GM5 is Mexico earthquake. The figures resulted with the fact that GM1 i.e the Kobe earthquake produces maximum drift in both the types of buildings and the lightweight concrete building suffers a drift which is approximately 12-15% less as compared to the normal-weight concrete building in both directions.

3.4 Performance comparison by static pushover analysis.

An incremental lateral load is given to the building in x and y directions in both types of concrete. The load in x-direction is termed as Px and the load in y-direction is termed as Py for both types of concrete. The performance point which is a well defined point on a scale measuring how much loss is caused by earthquake damage, is obtained from the curves resulting from pushover analysis and is used as a parameter to evaluate seismic performance of both the buildings. The performance point is plotted in the following curves between base shear and displacement with different building performance levels. The seismic performance assessment for the building is based on the position of the performance point in the following curves.

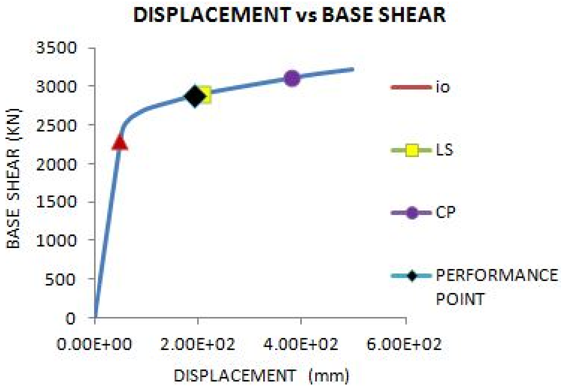


Fig. 8: Performance point for Px in normal-weight concrete building

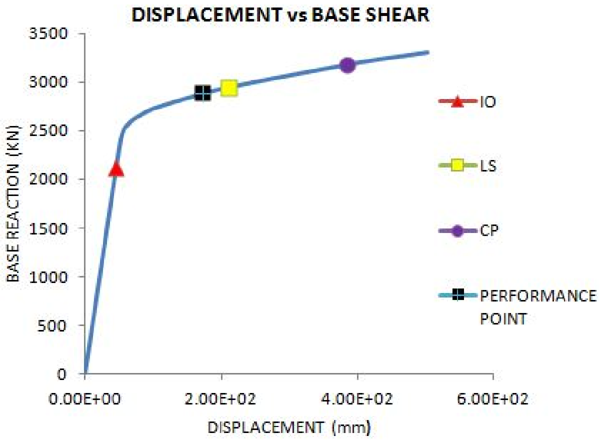


Fig. 9: Performance point for Px in lightweight concrete building

Performance point for Px in normal-weight concrete building is obtained at (191.003 , 2879.911) and plotted in Fig. 8 and that for the lightweight concrete building ,the performance point is obtained at (172.566 , 2884.913), shown in Fig. 9. The displacement axis is kept at a unit of 100mm which means 1.00E+02 is interpreted as 100mm and so on. From the above plots, it is seen that the performance point of the lightweight concrete building is at a lower displacement level than the conventional concrete for a base shear which is higher than the normal concrete building. Hence the lightweight concrete building shows a higher performance level under seismic load. Both the types of building are at Life safety level (LS) but the lightweight concrete building is at a lower LS level than the normal concrete building which is understood by observing the position of the performance point in Fig.8 and Fig.9.

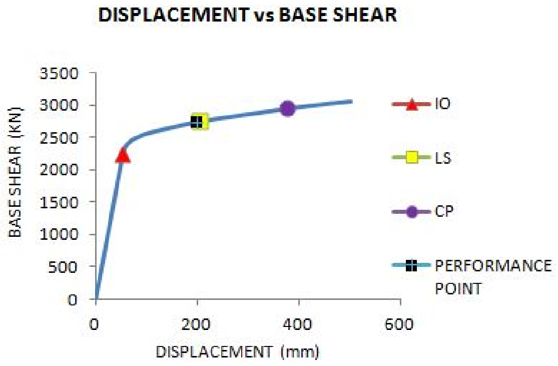


Fig. 10: Performance point for Py in normal-weight concrete building

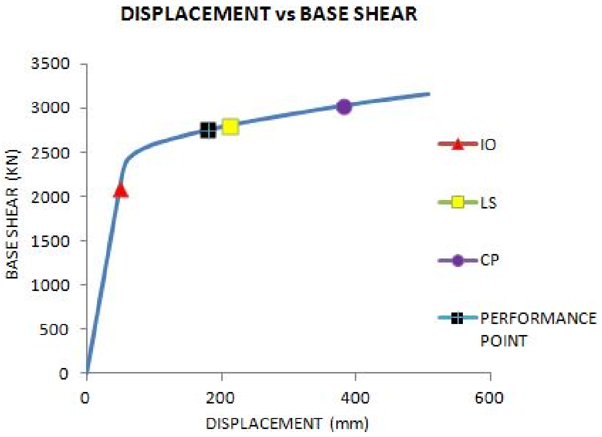


Fig. 11: Performance point for Py in lightweight concrete building

The Performance point for Py in normal-weight concrete building is obtained at (200.391 , 2741.976) and plotted in Fig. 10 and that for the lightweight concrete building ,the performance point is obtained at (181.2354 , 2750.448) shown in Fig. 11. Similarly as discussed for the case of Px in both the buildings, the graphs for Py also reveals the higher seismic performance of the lightweight concrete building than normal-weight concrete building which is evident from the position of the performance point in Fig. 10 and fig 11.

4. CONCLUSION

The following conclusions can be drawn from the results of this study:

1. Structural Lightweight concrete buildings can be used in

place of normal-weight concrete buildings with the same strength level to attain better seismic performance than conventional concrete buildings.

2. Under the action of a particular ground motion, lightweight concrete buildings suffer a considerably less inter-storey drift and consequently less deformation than normal-weight concrete buildings.
3. Due to the reduced dead load, the base shear force experienced by a lightweight concrete building is much lower than that experienced by a normal-weight concrete building.
4. Lightweight concrete buildings possess less displacement for a higher base shear and frequency than the conventional concrete buildings [5].
5. If the seismic performance of both the types of buildings can be optimized at a similar level, then the section of structural components and corresponding steel required for lightweight concrete buildings will be less as compared to normal concrete buildings and hence it will be much more economical than the conventional concrete buildings. This dimension can lead to a future scope of study in this field.

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