A Parametric Study on Seismic Response of Flat Slab Diagrid Structure

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Abstract - *This study is relevant to seismic performance of different types of flat slab diagrid structure. As flat slab have poor resistance to lateral loads & also the failure of flat slab buildings is mostly governed by the punching stresses at slab-column joints along the perimeter. For the study of such types flat slab structures, vertical columns are replaced by diagrid at the perimeter. In high rise structures use of exterior diagrid structural system proved to be more efficient in resisting lateral loads by axial action of its members. On the account of seismic response, time history analysis was carried out in ETABS computer code. The optimal uniform angle of diagrid for different types flat slab diagrid structure was suggested & various parameters such as time period, axial forces in diagrid, punching stresses in slab, max storey displacement, max storey drift & base shear were discussed. Diagrids are advantageous from structural as well as aesthetic point of view.*

***Key Words*: Types of flat slab, Diagrid, Seismic load, Optimal angle, Time history analysis**

1. INTRODUCTION

Flat slabs are the slabs which are supported directly on the columns omitting beams. It is a two-way slab bending in both the directions. To increase the shear strength of flat slabs different types construction can be done which are :- Flat plate, Drop panel, Column head, with combined Drop panel & Column head.

Flat slab have poor resistance against lateral loads due less lateral stiffness which results in excessive lateral displacement. Unbalanced moments concentration due to wind & earthquake loads near the edge columns is indeed a complex phenomenon. So, for the use of multi-storied flat slab structures, they must be equipped with lateral load resisting structural system.

Recent studies shows that the Diagrid structural system is effectively used to resist lateral loads in Tall structures. In Diagrid structural system all forces are transferred through a node, generating axial forces in the diagonal columns as compared to moment resisting frame system, in which external forces are transferred through beam-column junction, creating bending moments in vertical columns.

1.1 Objectives of the study

- The main objective of the study is to understand the behavior of different types of flat slab diagrid structures using linear time history analysis.
- To suggest the suitable angle of diagrid in Flat slab diagrid structure.
- To study response of Flat slab diagrid structures with increase in height of the building.
- To compare the results of different types of Flat slab diagrid building with normal Flat slab building.
- To study the response of building in terms of different parameters which are Time period, Axial forces in diagrid, Punching Stresses in slab, Base Shear, maximum storey Displacement and maximum storey Drift.

2. REVIEW OF LITERATURE

R.P. Apostolska, G.S. Necevska-Cvetanovska, J.P. Cvetanovska and N. Mircic (2008) Investigated the effects of designed modifications upon the dynamic characteristics as well as upon bearing and deformability of the flat-slab structures using time history analysis. The flat slab strengthened by perimeter beams and RC walls is having 40% less displacement and less fundamental period as compared to frame system. So, to limit the deformations in seismically prone areas & to increase the bearing capacity for flat slab structure under horizontal loads, modifications of such system are necessary by adding structural elements.

Subhajit Sen, Yogendra Singh (2010) Carried out non-linear static analysis of flat slab buildings, with and without considering the continuity of slab bottom reinforcement through column cages. The buildings was designed as per guidelines of IS 456:2000, ACI 318-08, EC 2:2004 and NZS 3101 (Part-1)-2006. In flat slab without edge beams, torsional portion of unbalanced moment causes excessive punching shear stress and design is governed by punching shear failure at exterior slab-column support while edge beams in flat slab transfer the unbalanced moment from exterior support reducing punching shear stress at slab column connection, which also reduces thickness of slab. Most of flat slab building are not ensuring Collapse

Prevention (CP) performance for MCE level of in high seismicity areas. So, continuity of slab bottom reinforcement improves the performance of flat slab buildings, significantly.

Nipan Bhandar Kayastha and Rama Debbarma (2019) Performed linear dynamic response spectrum analysis different flat slab structures provided with drop and capital. The brick masonry infill walls are modeled as braces using IS 1893-2016 guidelines. The flat slab building with drop & strengthened with shear wall is having least time period, storey displacement and storey drift. So, flat slab building modified by shear walls at outer periphery behaves excellently under earthquake loading even better than conventional RC frame building.

Kyoung Sun Moon (2008) Proposed the design provisions of diagrid structures having optimal grid geometries i.e. diagrids of uniform angles as well as gradually changing angles, depending on their heights (40,50,60,70,80 storey) and height to width (H/B) aspect ratios varying between 4 to 9. The stiffness based design methodology was adopted, and the total lateral displacement was contributed by bending and shears deformation. For uniform angle diagrid structures, the optimal angle increase with increase in height. The range of optimal angle is approximately between 60 to 70 degrees. For aspect ratio smaller than about 7, uniform angle diagrid structures are economical & for aspect ratio greater than about 7 gradually varying angle(steeper towards the base) diagrid structures are more economical in terms of material usage.

Giovanni Maria Montuori, Elena Mele, Giuseppe Brandonisio, Antonello De Luca (2013) Examined relative influence of stiffness and strength on the design outcomes are studied in terms of diagonal cross sections (C/S) of diagrid & its unit steel weight. In stiffness approach C/S are decided using bending to shear deformation ratio formulas, while in strength approach C/S are decided using axial forces forces formulas. Comparing diagonal cross sectional (C/S) area, it has been observed that for longer side of building, strength always prevails over stiffness at upper modules (i.e at 36, 45, 60 storey for diagonal angle of 64°,69°,79° respectively). For shorter side of building having low values of the diagonal angle (i.e. θ = 64°), the strength design is more stiff and drives to larger diagonal sections than stiffness design; while the opposite occurs in the case of steeper diagonal angles (i.e. θ = 79°), where the stiffness thoroughly governs the design of diagonals. For diagonal angle θ = 69°, the cross sections required for stiffness and strength are almost the same along shorter side elevation, indicates that where two design criteria tend to converge as this diagonal angle has the optimum value. So, strength and stiffness approaches are necessary & unavoidable in the design of diagrid structures.

Khushbu jani & Paresh V. Patel (2013) Performed analysis & design of (36,50,60,70,80 stories) Diagrid Steel structures as per IS 800-2007. Compared the distribution of gravity load with lateral load for each diagrid buildings and found that approximately 50-50% of gravity load is shared by exterior & interior frames while 97% of the lateral is resisted by exterior diagrid frames alone. It should be noted that internal columns are to be designed for vertical loads only. Diagrid structural system is more effective in resisting lateral loads, due to increase in lever arm of peripheral diagonal columns.

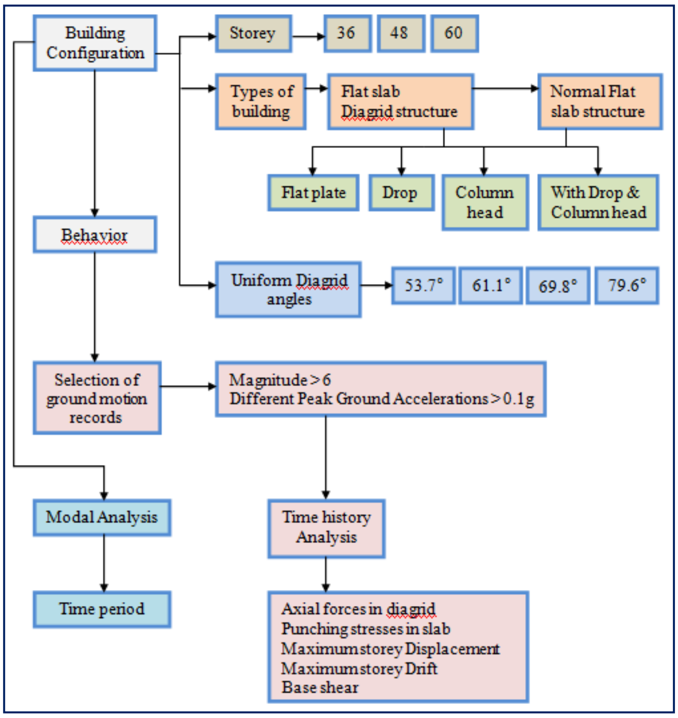
Swaral R. Naik and S. N. Desai (2019) Compared dynamic time history analysis of existing diagrid tall structure named Hearst tower, NY, USA, with similar dimensioned regular conventional structure. Modal analysis tells that the frequency of diagrid building in lesser plan dimensions is 2 times higher than regular conventional building which indicate that diagrid structures are stiffer than conventional structures. The diagrid building experiences 30-35% lesser lateral top displacement as compared with conventional building.

3. METHODOLOGY

The behavior of different types of Flat slab diagrid structures and normal Flat slab are studied by carrying out Modal Analysis & Time History Analysis in ETABS v18 software. The Stiffness based design methodology was used for the selection different diagrid angles.

3.1 Flow chart of work

Chart – 1:- Selection of different types of building models



3.2 List of Considered Time Histories

Table – 1 :- Selection of ground motion records

Sr. No	Event	Year	Station	Mw	PGA (g)
1	Imperial Valley - 06	1979	El Centro Array #4	6.53	0.48
2	Victoria, Mexico	1980	Cerro Prieto	6.33	0.64
3	Nahanni, Canada	1985	Site 1	6.76	1.20
4	India Burma border	1988	Diphu	7.20	0.33
5	Uttarkashi, IND	1991	Bhatwari	7.00	0.25
6	Cape Mendocino	1992	Cape Mendocino	7.01	1.50
7	Kobe, Japan	1995	Nishi Akashi	6.90	0.50
8	Chamoli, IND	1999	Gopeshwar	6.60	0.35
9	Bhuj kutch, IND	2001	Ahmedabad	7.00	0.11
10	Christchurch NZ	2011	Cathdral clg	6.20	0.47

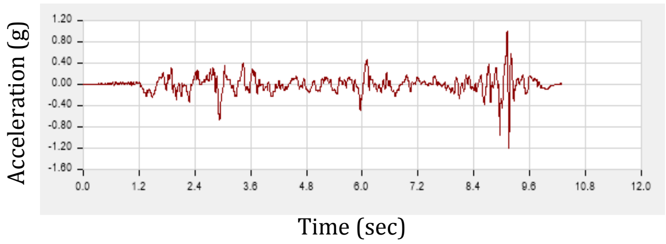


Fig – 1 :- Sample Graph of Nahanni Canada ground motion record, 1985

3.3 Stiffness Based Design methodology

By making the classical assumption that the building structure under lateral loads behaves as an ideal cantilevered tube, i.e. neglecting the shear lag effects, uniform tensile and compressive force distributions arise in the leeward and windward faces, respectively, as a consequence of the global overturning moment, while the faces parallel to the wind direction are subject to shear forces. The lateral stiffness of the structure, which counteracts these global actions, is given by the sum of two components, i.e. flexural and shear. Moon suggested simplified criteria for specifying the optimal ratio between flexural and shear stiffness components as a function of the building slenderness ratio H/B & diagonal angle in form of shear to bending deformation (s-factor) which is given by :-

$$s = \frac{0.19}{\tan\theta}\frac{H^2}{B^2}$$

The diagrid angles were selected on the basis of the ratio of shear to bending deformation i.e. the s-factor values which is derived in above subsection. Total four different angles are selected based on diagrid module & consecutive values of s-factor starting from 1 to 4 for 36 storey flat slab diagrid building & for same diagrid angles different stories i.e. 48 & 60 storey flat slab diagrid structure's response were studied. The selection of different diagrid angle with their respective s-factor values are shown in below table.

Table – 2 :- S-factor values for 36 storey flat slab diagrid structure

Total height of building in m =		108
Total width of building in m =		19.8
Module	Diagrid angle in degrees	S values
3	53.74	4.145
4	61.18	3.109
6	69.86	2.073
12	79.61	1.036

3.4 Nomenclature of Models

Models and Results will be presented using following nomenclature as by unique ID's shown in table below:-

Table – 3 :- Nomenclature of different Flat slab building models considered.

Stories Considered	Unique ID
36 Storey building	S36
48 Storey building	S48
60 Storey Building	S60
Types of Flat slab Diagrid building considered	Unique ID
Flate plate Diagrid building	DFP
Flat Slab Diagrid building with drop panels	DFD
Flat slab Diagrid building with column head	DFH
Flat slab Diagrid building with drop & column head	DFDH
Types of Normal Flat slab building considered	Unique ID
Flate plate building	NFP
Flat Slab building with drop panels	NFD
Flat Slab building with column head	NFH
Flat slab building with drop & column head	NFDH
Diagrid angles considered	Unique ID
Diagrid Module 3 having angle of 53.74°	M3
Diagrid Module 4 having angle of 61.18°	M4
Diagrid Module 6 having angle of 69.86°	M6
Diagrid Module 12 having angle of 79.61°	M12

4. MODELING DETAILS

In Flat slab diagrid structures, the spacing of diagrid is kept as 6.6 m i.e. one bay width on façade of the building. All buildings assigned with live load of 3 kN/m² and Floor Finish load of 2 kN/m² respectively. The Concrete grade for column and slab is assigned as M50 & rebar grade of reinforcement is assigned as Fe-415 and Steel grade of diagrid is assigned as Fe-345. In case of Flat slab diagrid structure with drop panels the drop panels are modified where intersection of diagrid with slab takes place.

Table – 3 :- Structural configuration of buildings

Plan size	19.8 m X 19.8 m
No of bays in X and Y direction	3
Spacing of bays in X and Y direction	6.6 m
Size of column	1500 mm X 1500 mm
Thickness of Flat plate slab	270 mm
Thickness of flat slab with Drop	200 mm
Thickness of flat slab with Column head	270 mm
Thickness of flat slab with drop & Column head	170 mm
Thickness of drop	70 mm
Thickness of drop with Column head	100 mm
Size of drop	3000 mm X 3000 mm
Size of column head at top	2000 mm X 2000 mm
Height of tapered column head	750 mm
Diagrid pipe section size	650 mm X 40 mm

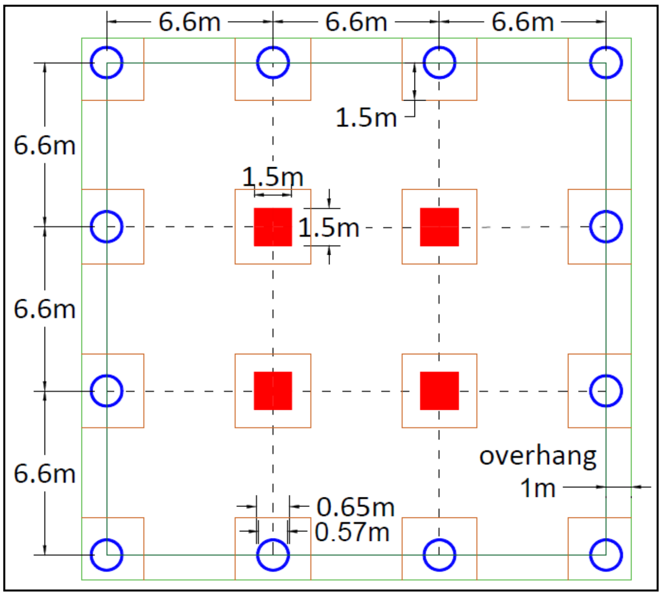


Fig – 2 :- Common drop panels location for all different diagrid angle at base and at it's module end.

5. RESULTS AND DISCUSSION

In this paper the results of 36 storey different types of Flat slab diagrid structure are presented and discussed.

5.1 Modal Analysis

In modal analysis time period is a governing factor for all the different types buildings. The value of time period depends upon building's flexibility and mass. In modal analysis a mass source i.e. the amount of assigned gravity load which participate in resisting lateral loads is taken as (DL+FF+0.25LL) for all building models.

5.1.1 Time period

In modal analysis, time period of first mode in different types of Flat slab diagrid structure are shown in below figures.

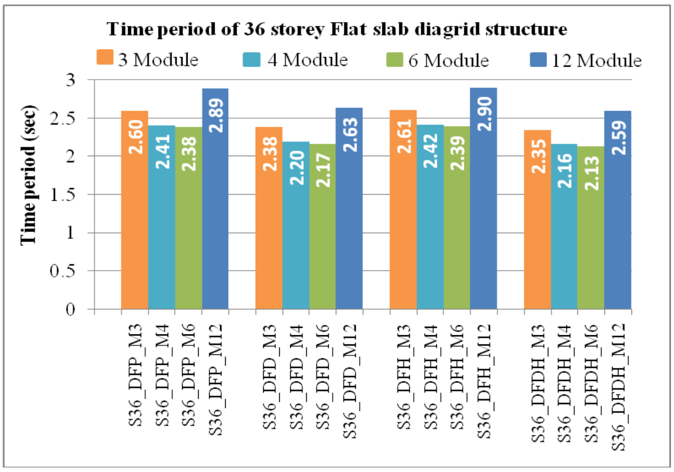


Chart – 1 :- Time period of 36 storey Flat slab diagrid structure

It can be observed that modal Time period of Flat slab diagrid structures decrease as diagonal slope increases except in 79.61° diagrid angle and the diagrid angle of 69.86° has least value in all different types of Flat slab construction.

5.2 Time history analysis

In linear Time History analysis different ground motion records from past earthquake event's station are incorporated in analysis software to predict the behavior of our building models when such type of earthquake occurs. The mean of absolute maximum values of 10 different ground motion records are taken for the preparation of results.

5.2.1 Axial forces in Diagrid

The axial forces are the forces that directly act in the line of action or say perpendicular to cross/sectional area in particular structural element. The axial forces in diagrid are observed at 1st number elevation view at two different location:- at middle & at corner for particular building model. Figure below shows the location of particular diagrid element for axial forces observation in all different type diagrid angles.

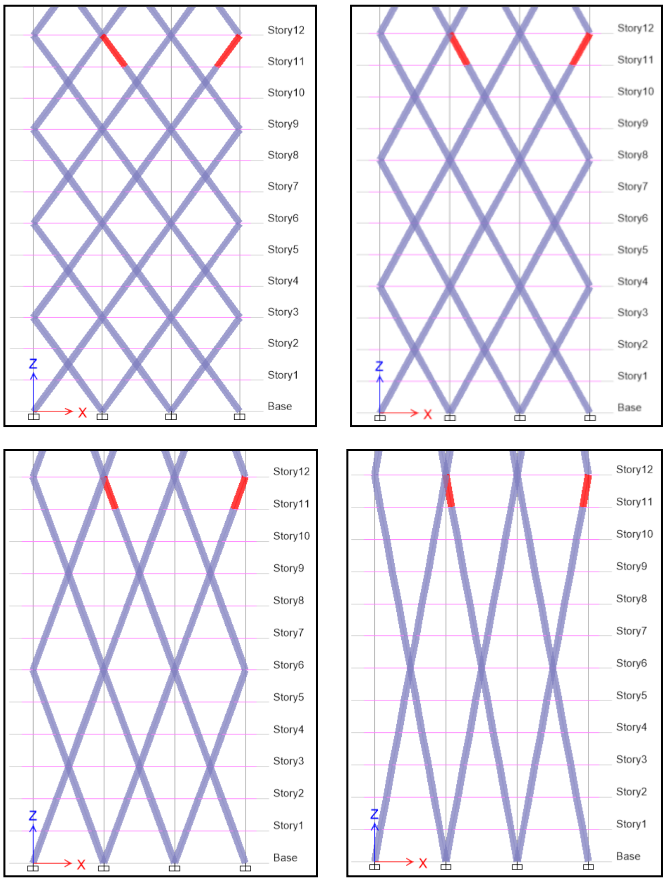


Fig – 3 :- ETABS modeling image showing axial forces observation location highlighted as red colored in, Left top – 53.74°, Right top – 61.18°, Left bottom – 69.86°, Right bottom – 79.61° Diagrid angle respectively.

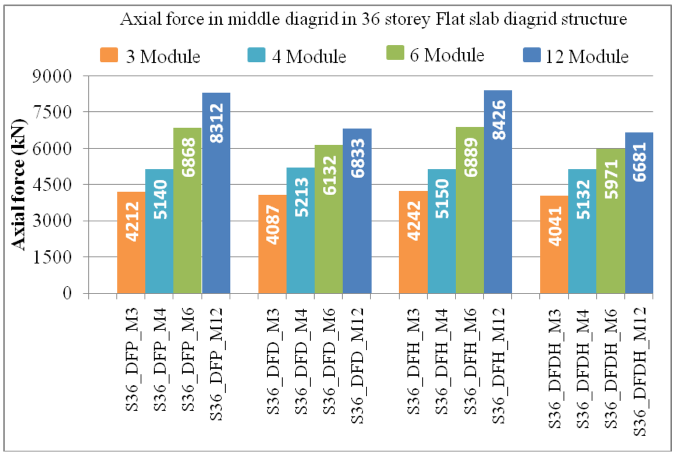


Chart – 2 :- Axial forces in 36 storey Flat slab diagrid structure.

From below chart it can be noted that with decrease in length of the diagrids located at middle its axial forces increases.

5.2.2 Punching stresses in slab

The punching stresses in slab are observed at same location i.e. at 24th storey in 36 storey different types of Flat slab diagrid structures. In ETABS shell stresses are results are studied for S11 direction stresses i.e. direct stresses acting in the slab in local x-direction with stresses occurring in the slab in local plane 1.

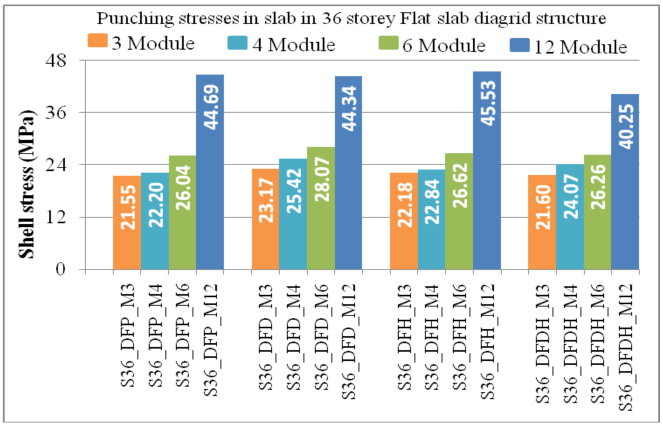


Chart – 3 :- Shell stresses in 36 storey Flat slab diagrid structure.

In a particular storey the shell stresses are observed to be maximum at slab-column junction & slab-diagrid intersection locations.

5.2.3 Base shear

The Base shear is the seismically active forces that act at the base of the building. The base shear also called as base reactions in particular direction are observed in x-direction.

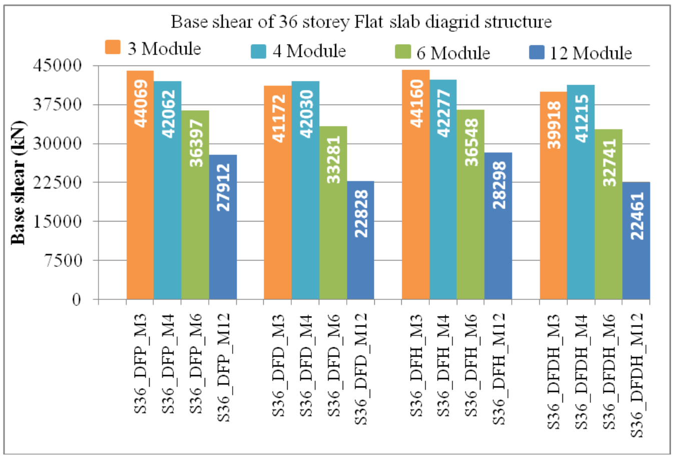


Chart – 4 :- Base shear of 36 storey Flat slab diagrid structure.

The Base reactions decrease with increase in diagrid angle as the axial forces in diagrid increase with increase in diagrid angle. Because in diagrid structural system, lateral and gravity loads are resisted by axial force in diagonal members. Also the weight of building decrease with increase in diagrid angle this is because with increase in diagrid angle the length of each diagrid decreases.

5.2.4 Displacement

The Displacement of particular building depends on amount of external action and its strength. The max storey displacement was observed in x-direction at top of the building.

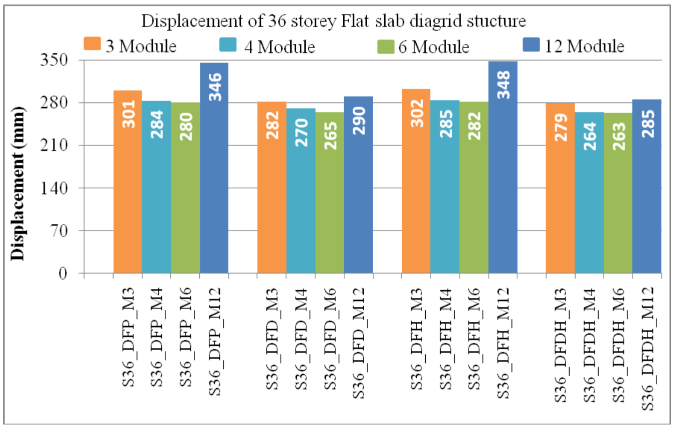


Chart – 5 :- Displacement of 36 storey Flat slab diagrid structure.

The lateral Displacement of building depends on its self weight. The building having less mass displaces more. From above chart it is surprisingly observed that the displacement of 61.18° & 69.86° diagrid angle building decrease with respect to 53.74° diagrid angle building model even though it mass decreases.

5.2.5 Storey- Drift

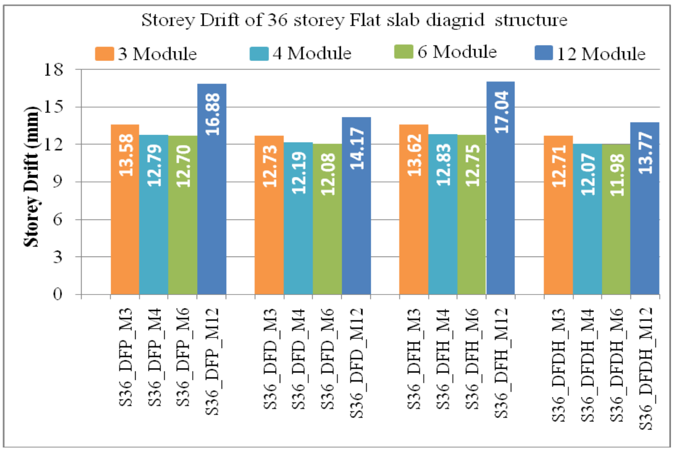


Chart – 6 :- Storey Drift of 36 storey Flat slab diagrid structure.

The maximum storey Drift in M3, M4 & M6 diagrid module are observed to approximately equal. In case M12 diagrid module the storey Drift is observed to be higher this is because of sudden change in diagrid module from M6 to M12. As in M3, M4 & M6 diagrid module storey stiffness is more as compared to M12 diagrid module. Also it should be noted that the max storey drift occurs in between stories but not at the top storey in all different types of Flat slab diagrid structures.

6. COMPARISON OF FLAT SLAB DIAGRID STRUCTURE WITH NORMAL FLAT SLAB STRUCTURE

The mean value of all four diagrid angles building with its respective types of height & types of Flat slab diagrid structures are compared with its respective type Normal Flat slab structures.

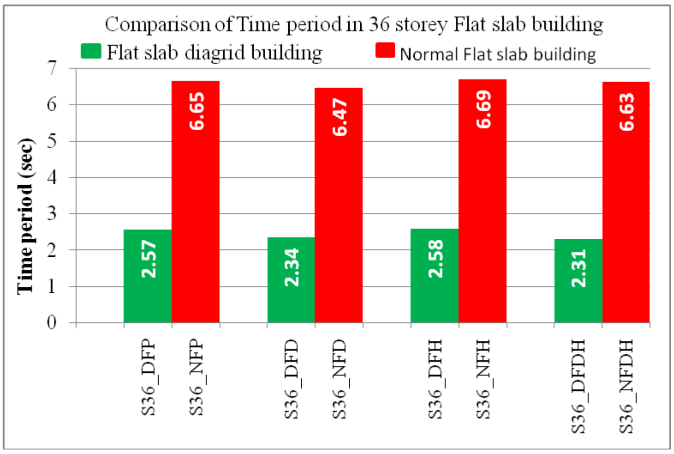


Chart – 7 :- Comparison of Time period in 36 storey Flat slab structure.

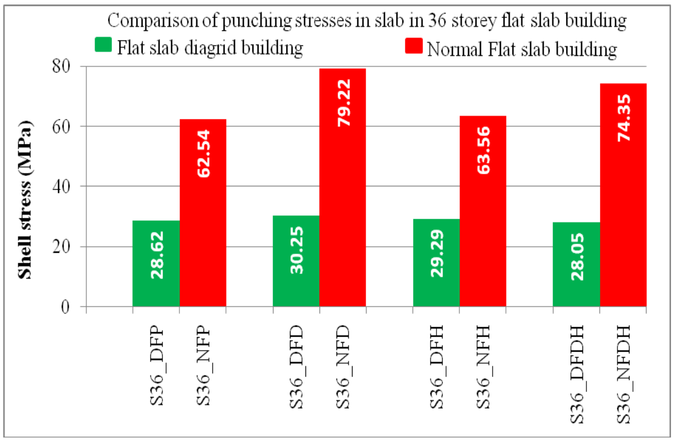


Chart – 8 :- Comparison of shell stresses in 36 storey Flat slab structure.

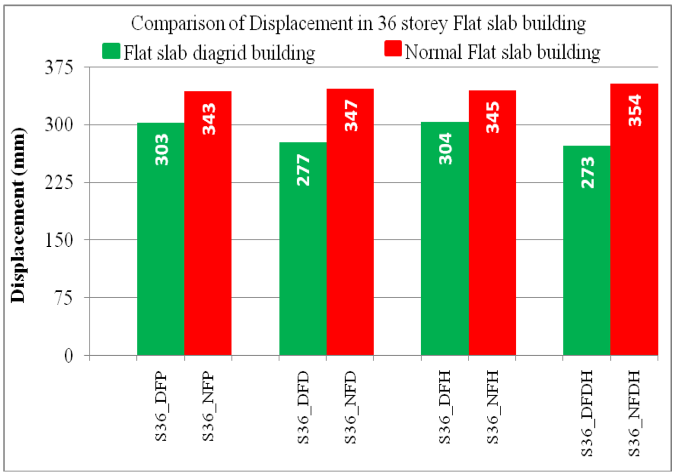


Chart – 9 :- Comparison of Displacement in 36 storey Flat slab structure.

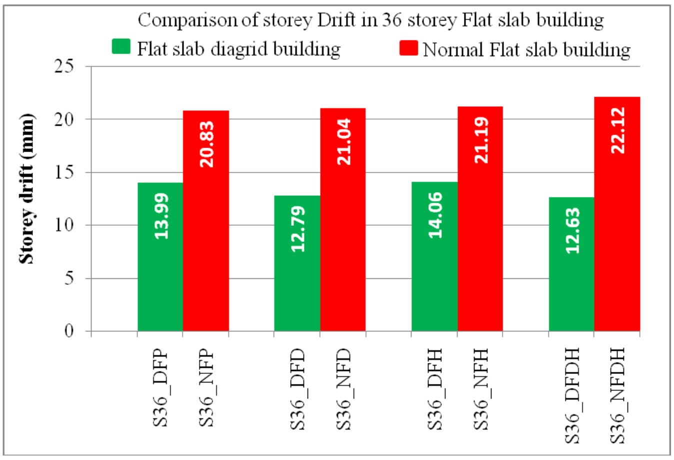


Chart – 10 :- Comparison of Storey Drift in 36 storey Flat slab structure.

Structure with lower natural frequency is flexible than higher natural frequency. The Time period of Flat slab diagrid structure is half of the Time period observed in normal Flat slab structure. As the time period is inverse of frequency, Flat slab diagrid structures are twice stiffer than normal Flat slab structures.

The punching stresses in Flat slab diagrid structures are 58% less than normal Flat slab structures. The Shell stresses in Flat slab diagrid structures are observed to be less due to incorporation of Diagrid structural system at the perimeter of the building instead of vertical columns which results in resisting higher seismic loads.

The Base shears in normal Flat slab structures are observed to be 72% less than Flat slab diagrid structure. This is because of difference in weight of the building as higher the weight of the building more is the Base shear. In case diagrid the steel material is assigned to it whereas in vertical columns concrete material is assigned. Also the numbers of diagrids in Flat slab diagrid structure are more as compared to numbers of vertical columns in normal Flat slab structure which are located on the façade of the building.

The maximum storey Drift of Flat slab diagrid structures are 28% less than normal Flat slab structure. So, less inter-storey movement is observed in Flat slab diagrid structures as compared to normal Flat slab structures. It should be observed that the maximum storey Drift in Flat slab diagrid structure occurs at higher storey whereas in normal Flat slab structure it is observed at lower storey for particular building models which conclude that normal Flat slab structures are more vulnerable to relative displacement at bottom stories.

7. CONCLUSIONS

- The diagrid angle of 69.86° i.e. 6 module diagrid has low modal Time period, less max storey Displacement & less max storey Drift as compared to all other diagrid angles which tends to be optimum in 36, 48, & 60 storey different types of Flat slab diagrid structures.

- The Axial forces in diagrid located at corner & middle generally increases with increase in diagrid angle. The Axial force in internal column decreases with increase in diagrid angle in all different types of Flat slab diagrid structure having different stories.

- The modal Time period, Base shear, max. storey Drift & diagrid's as well as internal column's Axial force of Flat slab diagrid structures with Drop panels and with Combined Drop panels & Column head seems to be less as compared Flat slab diagrid structures with Flat plate and with Column head with all different diagrid angles in 36, 48, & 60 storey building, as the stiffening of slab only near column decreases the mass of structure.

- The Displacement in 36 storey Flat slab diagrid structure with Drop panels and with Combined Drop panels & Column head is less as compared Flat slab diagrid structures with Flat plate and with Column head, whereas in 48 storey Flat slab diagrid structure it is opposite to results of 36 storey building and in 60 storey building the Displacement results tends to be nearly equal in all different types of Flat slab diagrid structures.

- The Slab's punching stresses are higher in Flat slab diagrid structure with Drop panels as due to decrease in slab thickness and surprisingly it was observed lesser in Flat slab diagrid structure with Drop panels & Column head even though its slab thickness is less as compared to all other slab types.

- The modal Time period, punching Stresses in slab & max. storey Drift of different types of Flat slab diagrid structure are less than normal Flat slab structure. So, Flat slab diagrid structures are stiffer than normal Flat slab structures as compared in 36, 48, & 60 stories building models respectively.

- The modal Time periods of both Flat slab diagrid structure as well as normal Flat slab structure increase with increase in building height whereas the Base shear of both Flat slab diagrid structure as well as normal Flat slab structure decreases with increase in building height.
- Storey Drift of Flat slab diagrid structure increases with increase in building height but in case of 79.61° diagrid angle it increases in 36 & 48 storey building and decreases in 60 storey building.

7. FUTURE SCOPE

- Different diagrid angles can be further studied according to strength based design methodology.
- Flat slab diagrid structure with infill walls can be studied.
- Flat slab diagrid structure with concrete material as diagrid to be studied.
- Nonlinear Static & Dynamic Analysis can be carried out for in depth understandings of collapse mechanism & behaviour of plastic hinges in flat slab diagrid structure.
- Strength and Stiffness irregularities can be considered for study in flat slab diagrid structure.
- Experimental work can be carried out in flat slab diagrid structure.
- Use of Prestressing in Flat slab can be studied by software analysis as well as by experimental work for flat slab diagrid structure.

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