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Influence of Slab Behavior on Diagrid Buildings

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ملخص البحث:

طريقة العناصر المحددة واحدة من أكثر الطرق المقبولة لتحديد سلوك المبانى وتمثيلها فراغيا. تمثيل البلاطات يعتبر عامل مهم لاجراء التحليل للمنشأت. يوجد طريقتين شائعيتين يستخدمهم المهندسيين الانشائيين لتمثيل البلاطات وهم كالتالى : تمثيل اعتبارات مرونة البلاطة و تمثيل اعتبارات صلابة البلاطة. وقد تم تنفيذ هذا البحث لفحص الاختلافات بين تمثيل سلوك البلاطات كبلاطات مرنة و بلاطات صلبة تحت تأثير أحمال الزلازل. وقد تم استخدام برنامجى SAP2000 وANSYS لتأكيد ملف الادخال لبيانات مبنى عالى مكون من 80 طابق بنظام انشائى من الشبكات القطرية. وقد تبين أن نتائج البرنامجين متوافقة ونتيجة لصعوبة التحليل باستخدام ANSYS تم تنفيذ النماذج المستخدمة على برنامج SAP2000 . تم اعتبار مجموعتين من المبانى العالية ذات الشبكات القطرية. المجموعة الأولى بها خمسة نماذج لها ميول مختلفة وموحدة خلال الارتفاع , أما المجموعة الثانية بها ستة نماذج لها نسبة ارتفاع الى عرض مختلفة و ميول موحدة للعناصر القطرية. وقد تم دراسة قيم الازاحة الجانبية عند القمة و قوى القص عند القاعدة لكل النماذج. و قد أظهرت النتائج أن التمثيل الصلب للبلاطات يتأثر بزاوية ميل العناصر القطرية و نسبة الارتفاع الى العرض.

Abstract

Finite element is one of the most acceptable tool for accurate simulation of building behavior and it is a reliable technique for 3D modelling. Slab modelling is an important parameter to make analysis. Two common methods of slab modelling are employed for structural engineers: flexible slabs (flexible diaphragm) and stiff slabs (rigid diaphragm). This research has been conducted to examine the difference between stiff and flexible slab behavior of diagrid buildings in existence of seismic load. SAP2000 and ANSYS software have been used to verify the input data file for 80-story diagrid tall building. The analysis results of the both software are consistent and due to the complication of ANSYS analysis, models have been performed using SAP2000. Two groups of diagrid tall buildings are considered: the first group has five models with various uniform inclinations of diagrid with the same height, while the second group has six models with various heights to width aspect ratios, and uniform diagrid inclination. The lateral displacement at the top and the base shear are studied through both groups. The results revealed that the stiff slab models are affected by diagrid inclinations and aspect ratio.

Keywords: Damping; Diagrid; Modal superposition; Seismic analysis; Stiff and flexible slabs.

1. Introduction

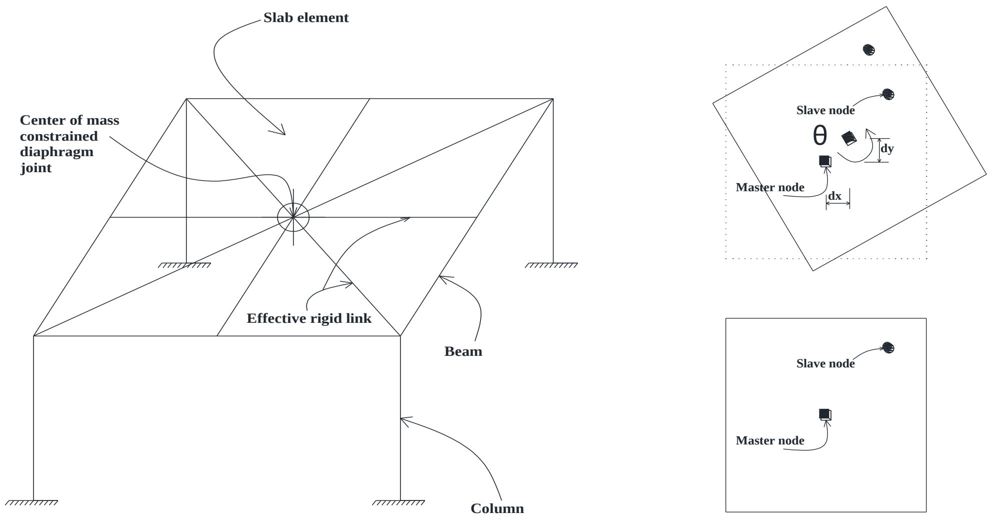
For seismic analysis of structures, the slabs play a major role in redistribution the lateral force. Considering the stiff or flexible solution of slab is an interesting topic. Stiff solution of slab behaves differently from flexible solution of its. The need for stiff solution of slab is increased to reduce the time and memory for analysis. A research papers were published to examine the behavior of slabs in modelling. Macleod [1] and Wilson et al. [2] suggested that floor slabs are assumed to be rigid in their planes with master node having three degrees of freedom to represent two in-plane translations and out of-plane rotation at all the other nodes or so-called slaved nodes in this floor slab. The slave nodes have three degrees of freedom similar to grid structures. No deformation in plane of floors is considered for structural analysis. Muto [3] simulated a beam have bending and shear deformation to consider the flexibility of slab. Jain [4] also, used the previous beam by [3] to examine the flexible behavior due to dynamic loads. Basu et al. [5] studied the differences in responses between modelling of slabs as flexible and rigid diaphragm for low-rise buildings.

Moon et al. [6] proposed a simple stiffness methodology for preliminary design diagrid building members ranging from 20 to 60 stories. The influence of the diagonal inclination on the behavior of diagrid structures is studied. It was found that, for 42 and 60-story diagrid buildings with an aspect ratio of about 5 and 7 respectively, the optimal diagrid inclination is about 55° to 75°. Mele et al. [7] studied the resisting mechanism of diagrid buildings due to gravity and wind loads, the effect of geometry on the behavior of the structure. Kamath et al. [8] examined the behavior of circular plan diagrid structure. Optimum angle of diagrid is increased with increasing aspect ratio. Shear rigidity decreases and time period increases with increasing angle of diagonal column. Zhao et al. [9] presented diagrid structures by controlling the bottom angle and the top angle by arc or straight diagonal. The bottom angle is the major variable in lateral load resistance. Optimal value of the top angle depends on aspect ratio. On the otherwise, aspect ratio has no effect on the bottom angle which is selected in between 55^{o}-65^{o} or 35^{o}-45^{o} respectively for diagrid structures with curved or varying angle straight. Gerasimidis et. al [10] proposed an optimization approach for the preliminary design of steel diagrid tall buildings using principal of virtual work.

This paper is initiated in order to enhance the differences in responses between stiff and flexible solution of slabs for three-dimension modelling of regular diagrid tall buildings. Different types of seismic linear analysis have been done through the permitted methods in [11] which are: equivalent lateral force, dynamic response spectrum, and dynamic time history. The cross section of diagrid elements is best configured due to an equivalent lateral force using stiffness-based design which was suggested by [6]. For stiffness-based design, bending to shear deformation at top is assumed to satisfy allowable lateral displacement at top (H/500) and inter-story drift to be around 0.003 to confirm the elastic behavior.

2. Rigid versus Flexible Slab Modelling

Considering rigid diaphragm, the slab is constrained to the horizontal degrees of freedom of all nodes at every level of the model center of mass using effective rigid link as shown in Fig. (1)(a) while, all these nodes are slaved to a master node which represents the global lateral movement of the diaphragm at that level. The lateral displacements for slaved nodes in both directions are coupled with the three horizontal degrees of freedom for the master node as shown in Fig. (1)(b). The stiff solution of slabs is considered by constrained the slab as rigid diaphragm. The final model has only three degrees of freedom for each level. The master node is placed at center of mass for each floor where the seismic force resultants are acting. The seismic force and mass are assigned directly to the master node. For flexible diaphragm, the slab is modelled as shell thin element with six degrees of freedom for each node.



(a) (b)

Fig. (1) Diaphragm modelling: (a) definition, (b) degrees of freedom.

3. Seismic Load Criteria

Different types of seismic linear analysis have been done through the permitted methods in [11]. These methods are equivalent lateral force, dynamic response spectrum, and dynamic time history (using modal superposition). Modal analysis is performed with number of modes achieving greater than or equal to 90% of mass participating ratio before seismic analysis. A forty number of modes are considered. All seismic loads are applied in x-axis. For the equivalent lateral force, the loads are computed using [11]. The design seismic parameters are design earthquake spectral response acceleration parameter at short period S_{DS} =0.2242, design earthquake spectral response acceleration parameter at 1 second S_{D1} =0.0816, building period coefficient C_t =0.02, constant depends on structure type x=0.75, response modification factor R=1.0, site class is C, importance factor I_e=1.0, and long period transition T_L =6 sec. For linear dynamic response spectrum, the response spectrum curve is generated as shown in Fig. (2). Incorporation the member end forces using the complete quadratic combination (CQC) technique. The response spectrum is generated for the same seismic parameters of equivalent lateral force. For linear dynamic time history (Modal superposition), the method for performing it's in [12] is importing the acceleration of earthquake as time history record, specify damping ratio, and select time step for analysis. The time step has been selected as 0.02 sec. The damping plays an important term in dynamic analysis. The best way to treat damping value in the model by using an equivalent damping equation by [13] which in the form:

$$[C] = \alpha[M] + \beta[K] \quad (1)$$

Where $[C]$= damping matrix of the structure, $[M]$= mass matrix of the structure, $[K]$= stiffness matrix of the structure, α and β can be obtained from the following equations:

$$\alpha = 2\xi_1\omega_1 - \beta\omega_1^2 \quad (2)$$

$$\beta = \frac{2\xi_1\omega_1 - 2\xi_m\omega_m}{\omega_1^2 - \omega_m^2} \quad (3)$$

Where ξ_1=damping ratio for the first mode, ξ_m=daping ratio for the mth significant higher mode considered for the analysis, ω_1= angular natural frequency for the first mode, ω_m=angular natural frequency for the m^{th} significant higher mode.
For first mode of vibration, Bernal et al. [14] proposed the following equation to compute the damping ratio for steel buildings as:

$$\xi = 1.2 + 4.26e^{-0.013H} \tag{4}$$

Cruz et al. [15] suggested the higher mode damping ratio using the following equation:

$$\xi(f) = \xi_1 \left[1 + \gamma(\frac{f_n}{f_1} - 1)\right] \tag{5}$$

Where $\gamma = 0.13$ for steel braced frame buildings which can be used for diagrid buildings, f_n=natural frequency for the nth significant mode, f_1=natural frequency for the first mode.

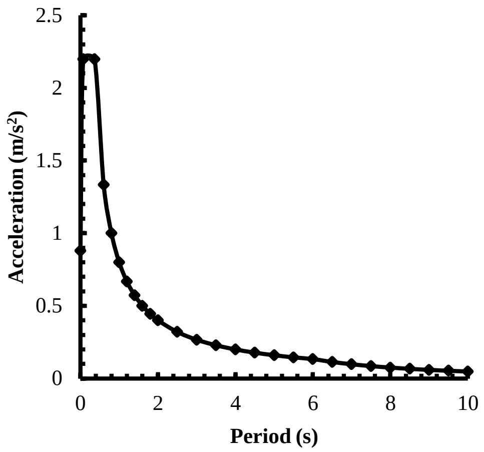
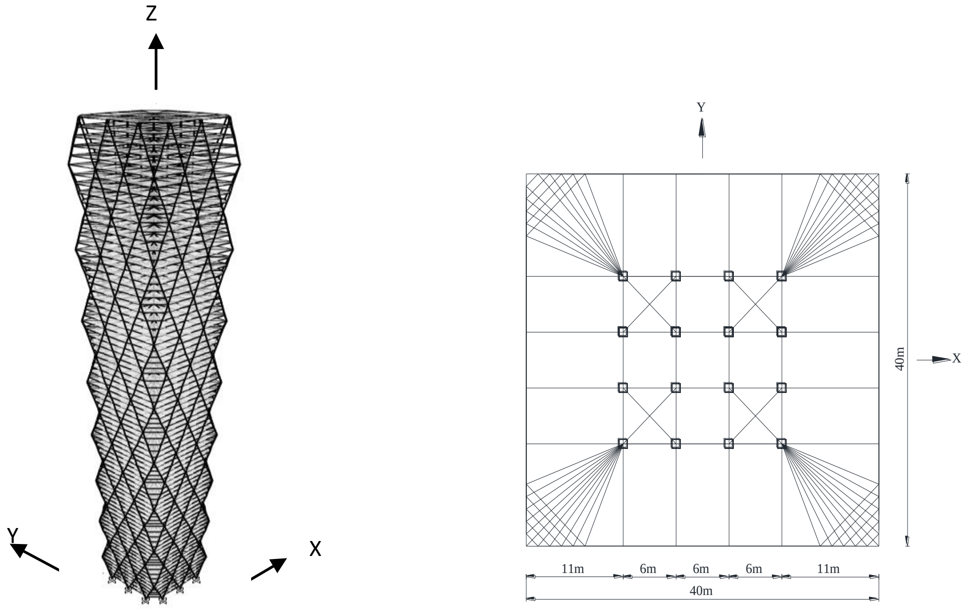


Fig. (2) Response spectrum curve.

4. Model Verification

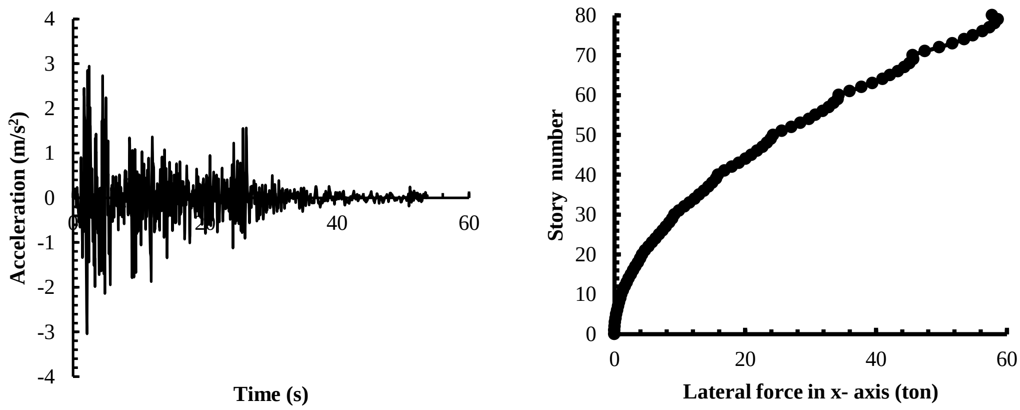
The verification is presented by analyzing an 80-story diagrid building using [12] and [16] software to emphasis the mathematical model for buildings. The finite element model in [12] depends on main elements which are frame element for beams and columns, shell element for slabs, and the base joints are restrained as fixed. The finite element model in [16] depends on main elements which are BEAM188 for beams and columns, SHELL181 for slabs, and the base joints are restrained as fixed. Seismic analysis is conducted using equivalent lateral force, and dynamic time history using modal superposition. A FORTRAN program is constructed to generate the data file texts for both [12] and [16]. Geometric parameter for verification building is shown in Table 1. 3D and cumulative plan for the verification model are shown in Fig. (3). For diagrid elements, custom made standard steel ASTM A500 [17] grade B, F_y = 289579.83 kN / m^2 circular tube with varying dimensions are used. Rectangular and square tube shape standard steel ASTM A500 grade B, F_y=317158.9 kN / m^2 for beams and vertical inner columns. Cross sections for diagrid and vertical inner columns are shown in Table 2. The Element types and material for all models are shown in Table 3. Meshing is done for all slabs with maximum size of 1.0 m. All slabs are modelled as concrete sections having compressive strength for concrete F_{cu} = 27579 kN / m^2 with 20 cm thickness. The used mass source is dead load plus 25% of live load for all models.

The ring beams cross section are rectangle tube (30 × 60 cm) with wall thicknesses (0.8 × 1.3 cm), and the inner beams cross section are rectangle tube (20 × 45 cm) with wall thicknesses (0.9 × 1.4 cm) for all models. Lateral seismic force for each floor is shown in Fig. (4)(a). El Centro acceleration record with base line correction is used for dynamic linear response history. The uncorrected record is extracted from [18] and the base line is corrected with equally time step 0.02 sec using [19]. The corrected record of El Centro is shown in Fig. (4)(b). The damping ratio for the first mode is computed by eq. (4). Modal analysis is done to extract the frequencies of the first and thirteen (significant higher mode for principal lateral modes of vibration) modes. The damping ratio for mode thirteen is computed by eq. (5). Damping is treated as Rayleigh damping using eqns. (1-3). The values of α and β are equal to 0.0149 and 0.006778 respectively. Fig. (5) shows the lateral displacement in x-axis due to equivalent seismic lateral force. Fig. (6) shows the lateral displacement response history in x-axis at top due to El-Centro record. These figures showed that the results obtained from [12] and [16] are almost identical. Both programs gave closer results.



(a) (b)

Fig. (3) Verification model views: (a) 3D view, and (b) cumulative plan view.



(a) (b)

Fig. (4) Eighty story diagrid building: (a) equivalent lateral force, and (b) acceleration history record for El Centro.

Table 1: Description for verification model.

Model description	Value
Height	320m
Plan width(square)	40m
Openings	Four openings 6 m × 6 m
Story height	4 m
Live load	$4.0kN/m^2$
Cover, finishing, and walls	$4.5kN/m^2$

Table 2: 80-story columns, and diagrid cross sections.

Story number	Dimensions[a] (cm)	Dimensions[b] (cm)
1-5	135×4.6	174.3×5.8
6-10	135×4.6	174.3×5.8
11-15	125×4.4	159.1×5.3
16-20	125×4.4	159.1×5.3
21-25	115×4.2	142.3×4.7
26-30	110×4.0	142.3×4.7
31-35	105×4.0	123.9×4.1
36-40	095×3.8	123.9×4.1
41-45	095×3.8	104.2×3.5
46-50	090×3.6	104.2×3.5
51-55	085×3.4	96.5×3.2
56-60	080×3.2	96.5×3.2
61-65	075×3.0	84.0×2.8
66-70	065×2.6	84.0×2.8
71-75	060×2.4	63.1×2.1
76-80	055×2.2	63.1×2.1

[a]Dimensions are referred to inner vertical column (outer width × thickness).
[b]Dimensions are referred to diagrid elements (outer diameter × thickness).

Table 3: Element types and material properties.

Structure element	Type of element	Degree of freedom for each joint	Material type	E (kN/m^2)	Specific weight (kN/m^3)
Slab	3 or 4 node shell	6	Concrete	24855578	25.56
Diagrid	Line element	6	Steel	200×10^6	76.97
Columns	Line element	6	Steel	200×10^6	76.97
Beams	Line element	6	Steel	200×10^6	76.97

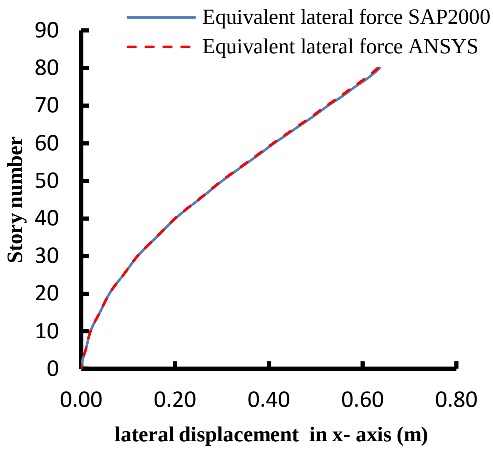


Fig. (5) Displacement for 80 story diagrid building.

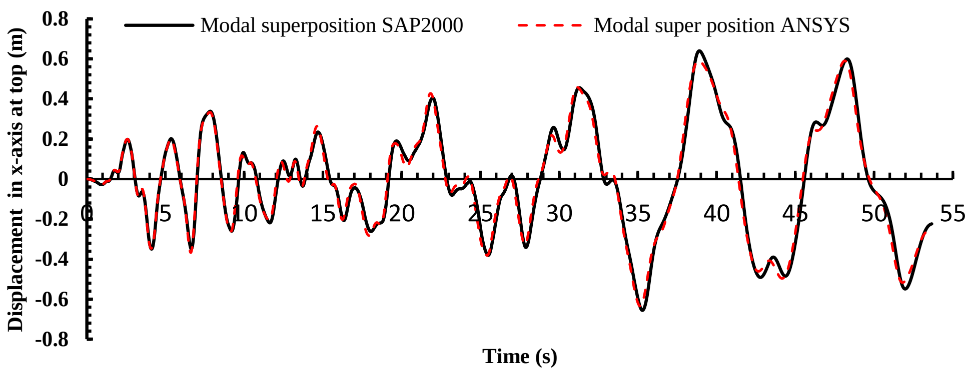


Fig. (6) Displacement history at top due to El Centro for 80 story diagrid building.

5. Models Identification

Two groups of diagrid buildings are studied to examine the difference between stiff and flexible solution of slab. The first group consists of five models with various uniform diagrid angles with the same height of 320m. The five models have diagrid angle of 50.19° for the module of four story, 60.94° for the module of six-story, 67.38° for the module of eight-story, 71.56° for the module of ten-story, and 80.53° for the module of twenty-story. The first group has typical story height 4.0 m. The second group consists of six models which have varied aspect ratios from 6.0 to 3.0 with typical story height 3.0m. The buildings height ranges from 240 m to 120 m. The load from cover, finishing, and walls are assumed to be 4.5 kN / m^2 for the two groups. The two groups are subjected to live load 4.0 kN / m^2. Plan dimensions for buildings are 40 m × 40 m with four openings 6.0 m × 6.0 m, and 16 core columns. X-Z, and cumulative plan views for the two groups are shown in Figs. (7) to (9). Damping parameters are shown in Table 4. The buildings are designed using stiffness-based method which is suggested by [6] to satisfy constrained displacement (H/500) and maximum inter-story drift around 0.003 due to equivalent static load. A square tube with outer dimensions varying between 135 cm × 135 cm and 50 cm × 50 cm and wall thickness ranges between 4.6 cm and 2.0 cm are used for the 16 core vertical columns. Diagrid circular steel sections of outer-diameter varying between 284.0 cm and 25.3 cm with wall thickness ranges between 9.5 cm, and 0.8 cm are used. The ratio between outer-diameter to thickness is almost equal to 30. Cross sections area for diagrid elements are shown in Fig. (10).

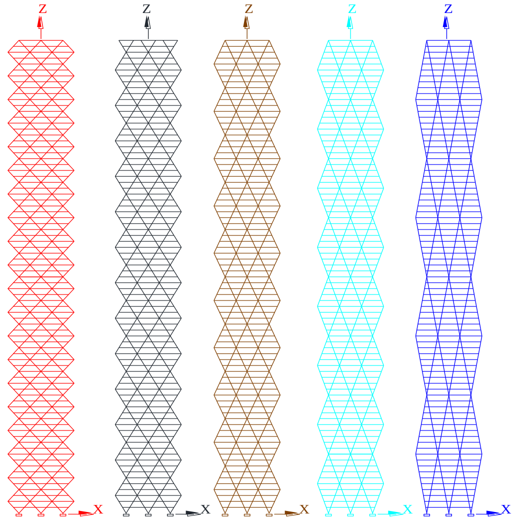
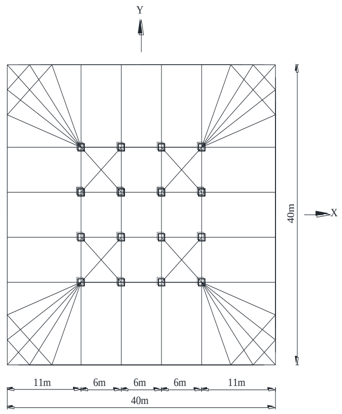
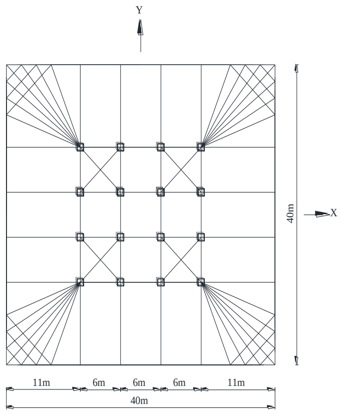


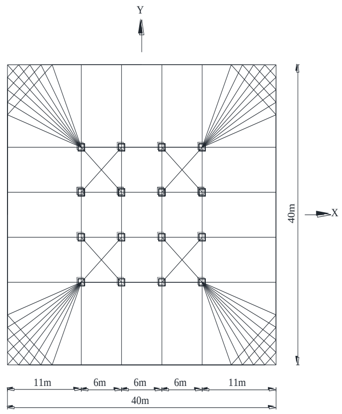
Fig. (7) Group 1 (X-Z views for diagrid buildings with 320m height).



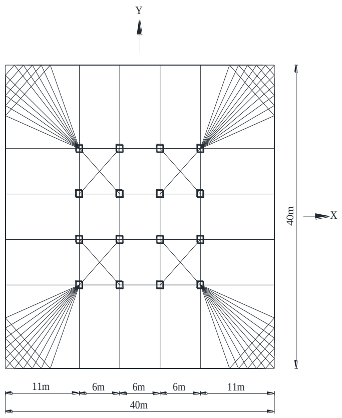
(a)



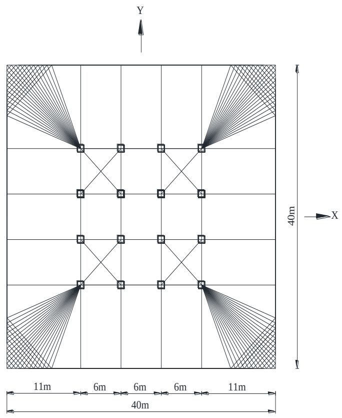
(b)



(c)

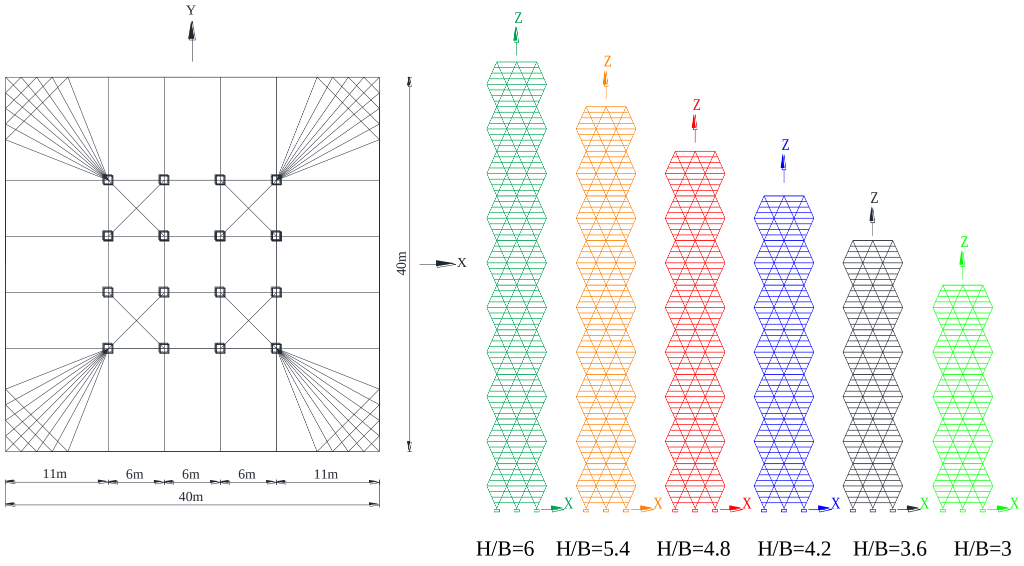


(d)



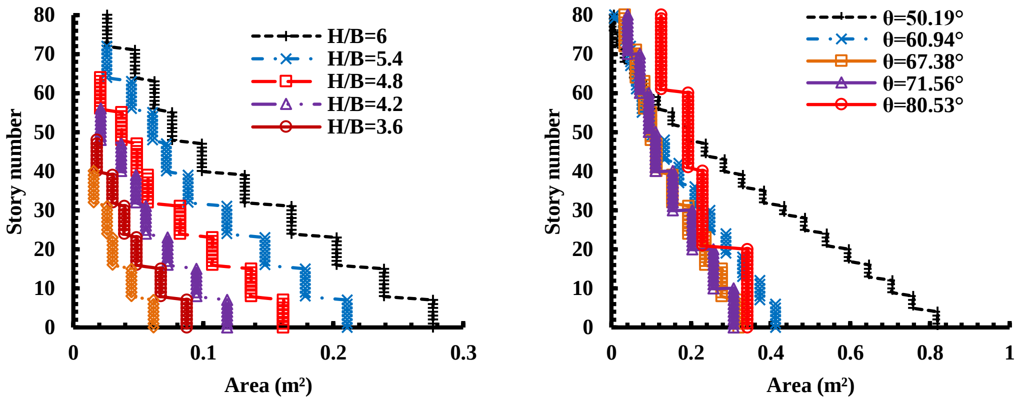
(e)

Fig. (8) Cumulative plan view of group 1: (a) Diagrid angle 50.19°, (b) Diagrid angle 60.94°, (c) Diagrid angle 67.38°, (d) Diagrid angle 71.56°, (e) Diagrid angle 80.5°.



(a) (b)

Fig. (9) Group 2 diagrid buildings: (a) Cumulative plan view, and (b) X-Z view.



(a) (b)

Fig. (10) Area of diagrid element each floor: (a) Group 1, (b) Group 2.

Table 4: Damping parameters for all models.

Aspect ratio	Diagrid angle	f_1	f_{13}	ξ_1	ξ_{13}	α	β
8	50.19	0.1246545	1.855167	1.27	3.56	0.0162	0.005989
8	60.94	0.119826	1.8571253	1.27	3.66	0.0156	0.006158
8	67.38	0.1167132	1.6835421	1.27	3.49	0.0152	0.006463
8	71.56	0.1162294	1.4453491	1.27	3.16	0.0149	0.006778
8	80.53	0.10966	1.0149845	1.27	2.63	0.0137	0.00791
6	60.94	0.152898	2.005533	1.39	3.58	0.0216	0.00546
5.4	60.94	0.1655902	2.0082299	1.46	3.62	0.0244	0.005498
4.8	60.94	0.1816202	2.02333	1.55	3.59	0.0282	0.005473
4.2	60.94	0.2022814	2.043768	1.68	3.68	0.0334	0.005564
3.6	60.94	0.2295229	2.0753744	1.86	3.8	0.0419	0.005476
3	60.94	0.2638739	2.1171617	2.1	4.04	0.0531	0.005802

6. Results Analysis

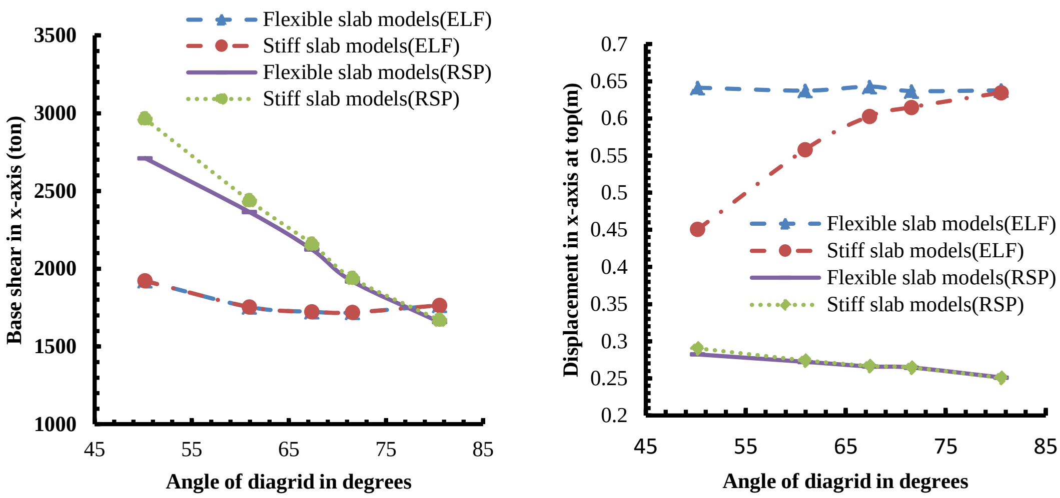
The results of lateral displacement and base shear for different models with different angles and different aspect ratios due to equivalent lateral force (ELF), dynamic response spectrum (RSP), and linear time history using [12] are introduced.

Referring to Figs. (11), and (12), one can be observed that:

For equivalent lateral force, an increase for angle of diagrid led to reduce the deviation of lateral displacement at top between flexible slab and stiff slab models. Base shear does not change for the both cases. The deviations between stiff and flexible slabs for lateral displacement at top are ranged between 29.75 and 0.5 % for the models with inclinations between 50.19° and 80.53°. For group 2, the deviations are ranged between 6.22 and 1.5 % accompanied with the decreasing in aspect ratio. The results indicated that, for response spectrum, the deviation of lateral displacement is not significant between flexible and stiff slab model with changing of diagrid angle or aspect ratios. The deviation of base shear between flexible and stiff slab model is increased with the increasing of height, and the decreasing of diagrid angle. Lateral displacement for dynamic response spectrum is lower than for equivalent static load. For tall diagrid buildings, base shear for dynamic response spectrum is greater than for equivalent lateral force. Base shear for equivalent lateral force may pass over for dynamic response spectrum for higher inclinations of diagrid. Base shear for equivalent static may pass over base shear for dynamic response spectrum for low-rise diagrid buildings, and high-rise buildings with high diagrid inclinations.

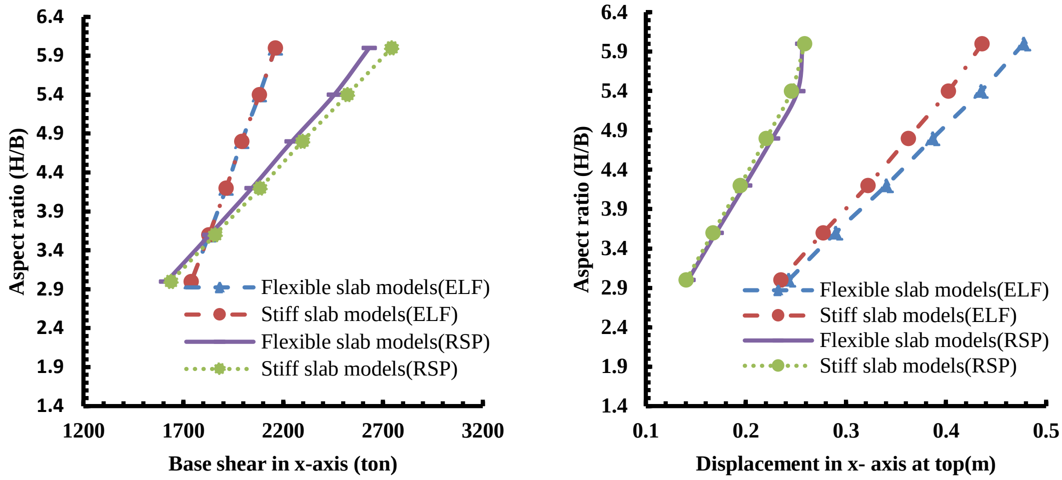
Figs. from (13) till (23) indicate that:

For linear dynamic time history of El-Centro, the lateral displacement, and base shear history is almost identical for higher angles of diagrid, and low aspect ratios. Angle of diagrid has no influence effect between flexible and stiff slab model on low-rise diagrid buildings.



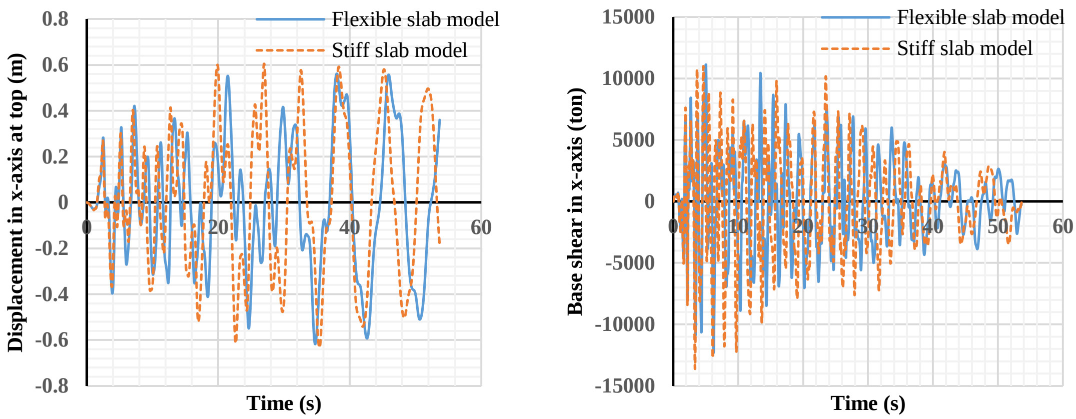
(a) (b)

Fig. (11) Group 1: (a) lateral displacement at top, and (b) Base shear.



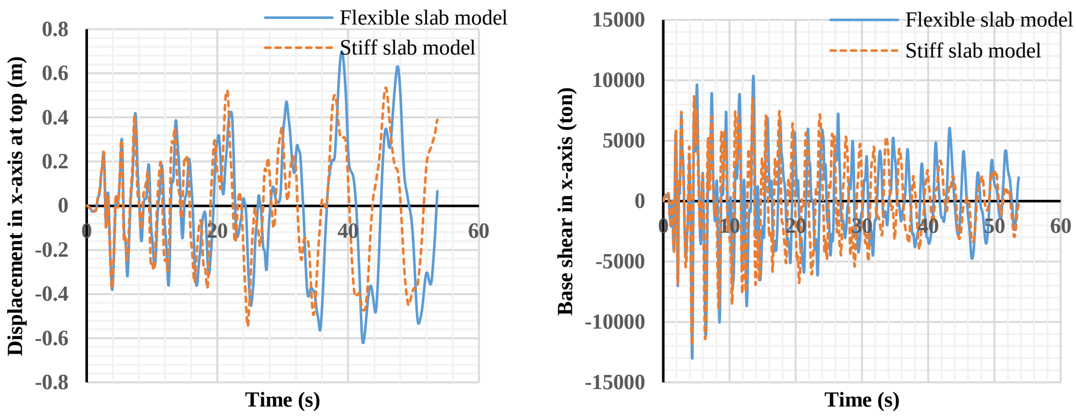
(a) (b)

Fig. (12) Group 2: (a) lateral displacement at top, and (b) base shear.



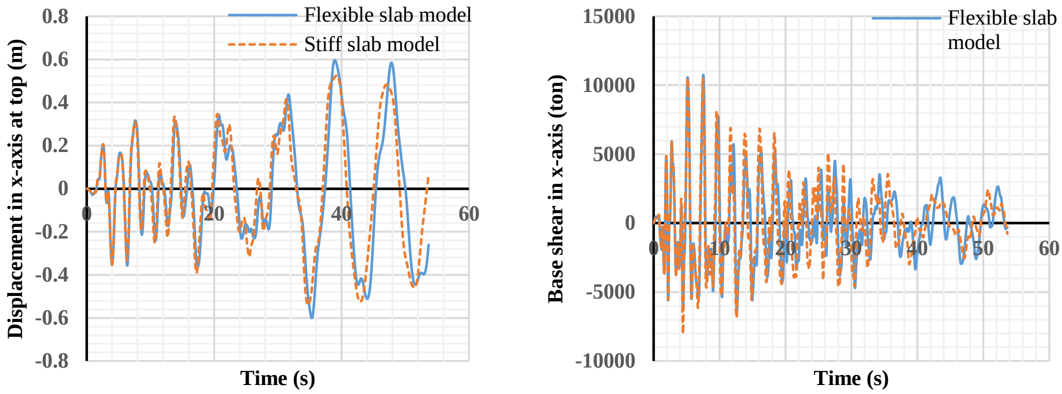
(a) (b)

Fig. (13) Building with diagrid inclination 50.19°: (a) Displacement, and (b) Base shear.



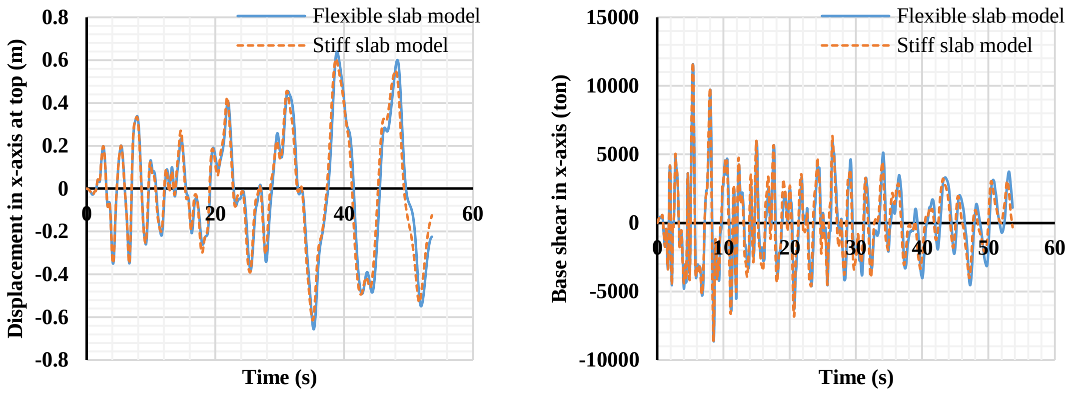
(a) (b)

Fig. (14) Building with diagrid inclination 60.94°: (a) Displacement, and (b) Base shear.



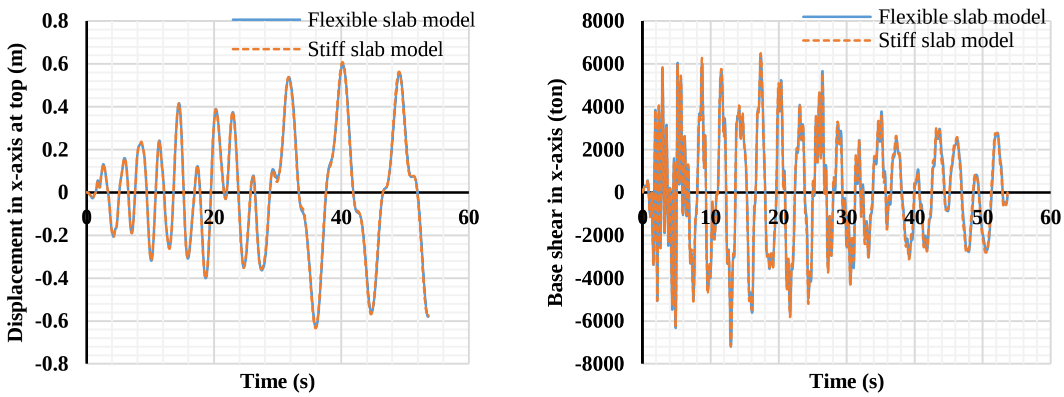
(a) (b)

Fig. (15) Building with diagrid inclination 67.38°: (a) Displacement, and (b) Base shear.



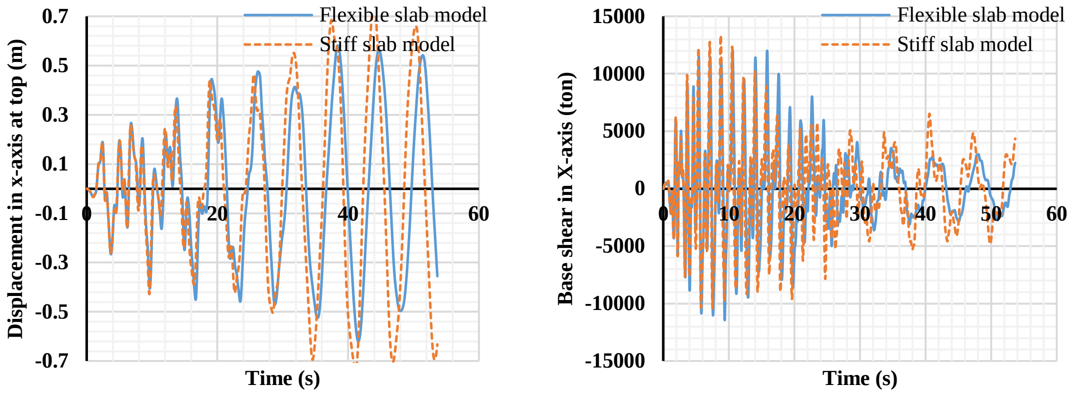
(a) (b)

Fig. (16) Building with diagrid inclination 71.56°: (a) Displacement, and (b) Base shear.



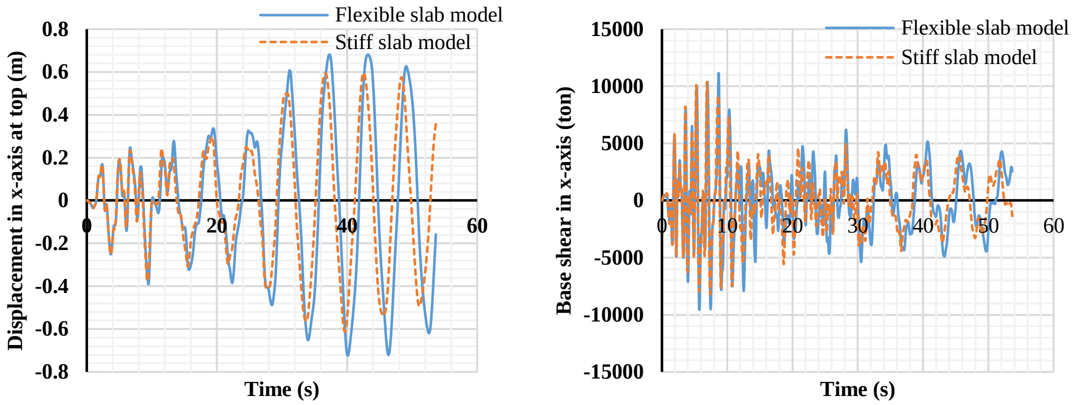
(a) (b)

Fig. (17) Building with diagrid angle 80.53°: (a) Displacement, and (b) Base shear.



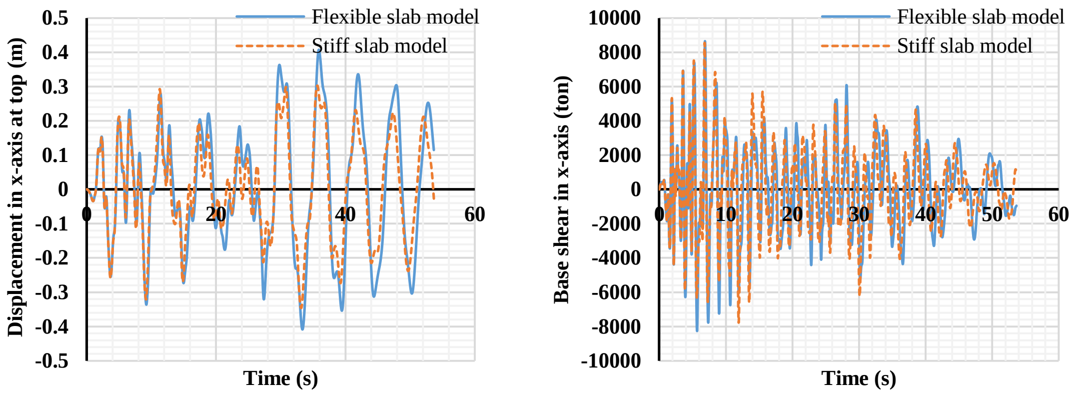
(a) (b)

Fig. (18) Building with aspect ratio 6: (a) Displacement, and (b) Base shear.



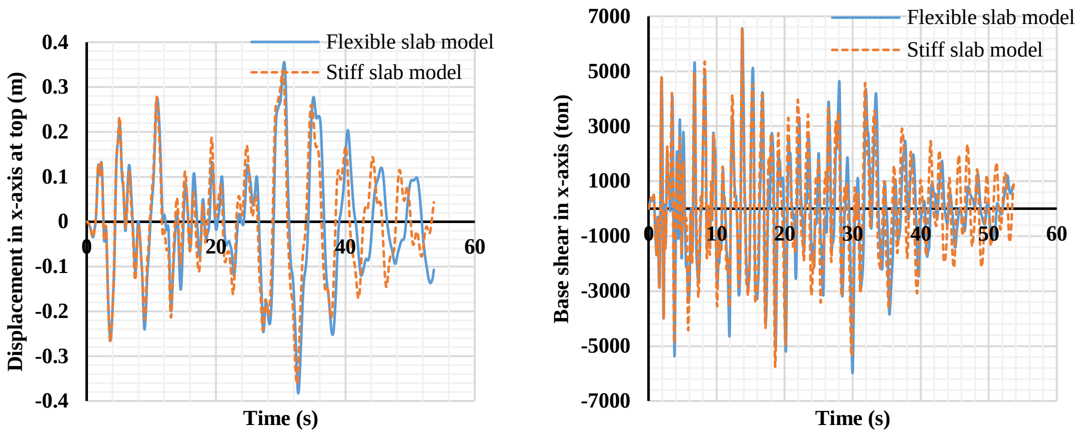
(a) (b)

Fig. (19) Building with aspect ratio 5.4: (a) Displacement, and (b) Base shear.



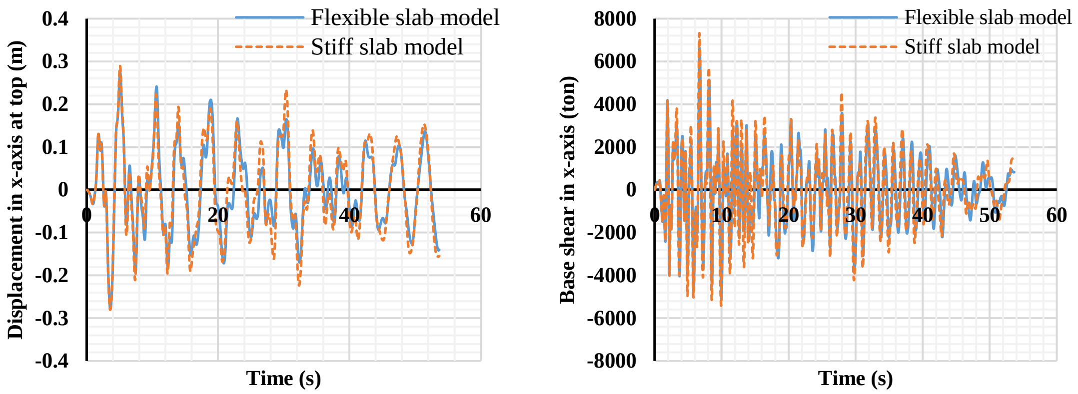
(a) (b)

Fig. (20) Building with aspect ratio 4.8: (a) Displacement, and (b) Base shear.



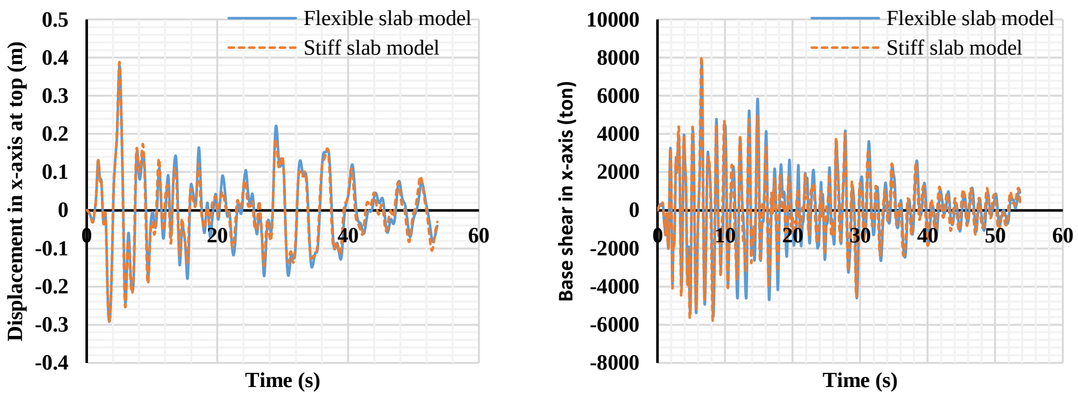
(a) (b)

Fig. (21) Building with aspect ratio 4.2: (a) Displacement, and (b) Base shear.



(a) (b)

Fig. (22) Building with aspect ratio 3.6: (a) Displacement, and (b) Base shear.



(a) (b)

Fig. (23) Building with aspect ratio 3: (a) Displacement, and (b) Base shear.

7. Conclusions

The study numerically investigated the slab behavior on diagrid buildings. The results revealed that stiff modelling of slabs is more acceptable for various low rise diagrid buildings and high rise diagrid buildings with steeper angles. Angle of diagrid affects the results of high rise diagrid buildings. Flexible solution of slabs is the more accurate for finite element analysis but it engrosses a large executed time for analysis. It needs a large internal memory. The analysis is faster if stiff solution of slabs is considered. Stiff slabs are affected by the diagrid angle and the aspect ratio. For dynamic analysis, stiff slab models give base shear greater than flexible slab models.

8. References

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