Seismic Resistivity Assessment of a Diagrid Exoskeleton Structure Based on Probabilistic Nonlinear Dynamic Analysis

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Abstract—**Diagrid exoskeleton structures have recently come to the forefront as a possible asset for an integrated remodelling strategy for existing buildings, where structural safety, energy efficiency, environmental sustainability, and architectural excellence are all enhanced. This research study examines the seismic performance of diagrid structures and their capacity to dampen earthquake-induced vibrations while considering a module set and member sizing methodology. This methodology considers the influence of the diagonal angle on the behaviour of the diagrid system under seismic loading. The models are created and analysed using general purpose FE software, ABAQUS. The models' nonlinear finite element analysis is broken down into different phases. In the first stage, the FEM is subjected to response spectrum testing with the goal of comparing their performance under earthquake. The second stage is the response spectrum test, allowing structural safety to be determined. In addition, the Peak Floor Acceleration (PFA) at various floors is determined using a mode superposition approach. The results show that, in addition to displacement and deformation control, significant reductions of the internal forces in the exoskeletal system are observed.**

Keywords—**exoskeleton structure, diagrid structure, seismic resistance, nonlinear dynamic analysis**

I. Introduction

Despite its complexity and ambiguities, earthquake phenomena are becoming more widely recognised, and as a result, building codes are changing. A greater effort has been made in the past thirty years to evaluate the seismic resilience of various buildings. However, due to the variety of structures and the complexity of the impact of many elements and causes on the seismic susceptibility of buildings, preparation and standardisation are required [1]. Nowadays, we can generate spatial computational models that are remarkably like actual structures owing to advances in computer technology.

The main objective of the current research is to study the seismic performance of buildings designed according to the new seismic regulations. A review of the literature shows that there are insufficient reports of seismic safety studies for buildings. In this study, a plan for a comprehensive study of the seismic performance of such buildings is presented. The following types of structural forms are identified for study: (a) moment-bearing concrete frame system and (b) diagrid exoskeleton structures with concrete shear wall system.

The seismic performance of a structure determines the extent of an earthquake damage. The uniform hazard spectrum is recommended as the goal spectrum in most seismic codes. Based on research in this field, the conditional mean spectrum can be more beneficial than the hazard spectrum. The uniform hazard spectrum assumption is responsible for the significant spectral values found in an earthquake's specific spectrum. The mean spectrum shows that the expected value of a rotation is greater than the observed value [2].

Diagrid exoskeleton structure is considered as one of the unconventional construction approaches. The viability of using a diagrid exoskeleton structure for seismic protection is especially noteworthy of research in earthquake-prone areas [3] where new structural control systems are essential to the creation of a resilient built environment [4–7]. Exoskeleton structure is a term with a biomimetic meaning that refers to a self-supporting structural system that is externally located and adequately attached to a primary inner structure, with the latter, relatively speaking, being reinforced, or protected by means of this linkage. Diagrid exoskeleton structures have lately come to the forefront as a possible asset for an integrated remodelling strategy for existing buildings, where structural safety, energy efficiency, environmental sustainability, and architectural excellence are all enhanced [6, 8–9].

This paper examines the seismic performance of exoskeleton structures and their capacity to dampen earthquake-induced vibrations while considering a module set and member sizing methodology. This methodology considers the influence of the diagonal angle on the

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behaviour of the diagrid system under seismic loading. The goal is to understand how a rigid coupling affects the dynamic response of the structure and whether it may be used to achieve vibration control goals. Dynamic coupling is a huge factor in how well the exoskeleton will hold up. In this study, three 3D finite element models were developed to analyse the seismic resistance of high-rise diagrid exoskeleton structures and conventional high-rise structure. The models were calibrated against experimental results and used for a parameter study to understand the effects of different parameters on seismic resistance. The models were analysed for two types of seismic excitation and parameters studied included floor displacement, inter-storey drift ratio, floor shear forces, and energy dissipation percentage. The study aimed to find a balanced module set and demonstrate the efficiency of diagrid exoskeleton structures compared to conventional structures using pushover analysis, modal superposition, and nonlinear dynamic analysis

II. Diagrid Exoskeleton Structure

A. *Modelling of Diagrid Exoskeleton Structure*

In this research work, three Three-Dimensional (3D) Finite Element model (FE) for a diagrid exoskeleton structure were developed. The models were created and analysed using the general-purpose FE software ABAQUS. The modelling techniques of diagrid exoskeleton structures are discussed in the following sections.

B. *Model Description*

Three cases were used in the research: (a) a standard RC structure-model 1; (b) a two-module diagrid exoskeleton-model 2; (c) a four-module diagrid exoskeleton-model 3. These are shown in Fig. 1. All FEM simulations were performed with the finite element software ABAQUS. Fig. 2 illustrate floor layout showing beam arrangement of three models.

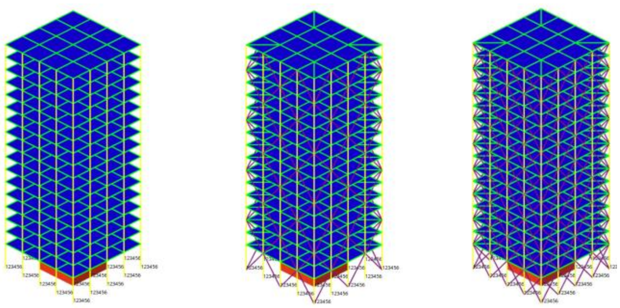


Fig. 1. ABAQUS models.

A 17-storey building with a square floor plan of 24.5 m × 24.5 m and a total area of 600.25 m^2 was used as a benchmark model. The floor plan layout is shown in Fig. 2. The structures have an aspect ratio of 1:1 in both the x and y directions. The total height of the buildings is 65 m. The single-storey construction height is 3.6 m, except for the ground floor which has a construction height of 7.4 m.

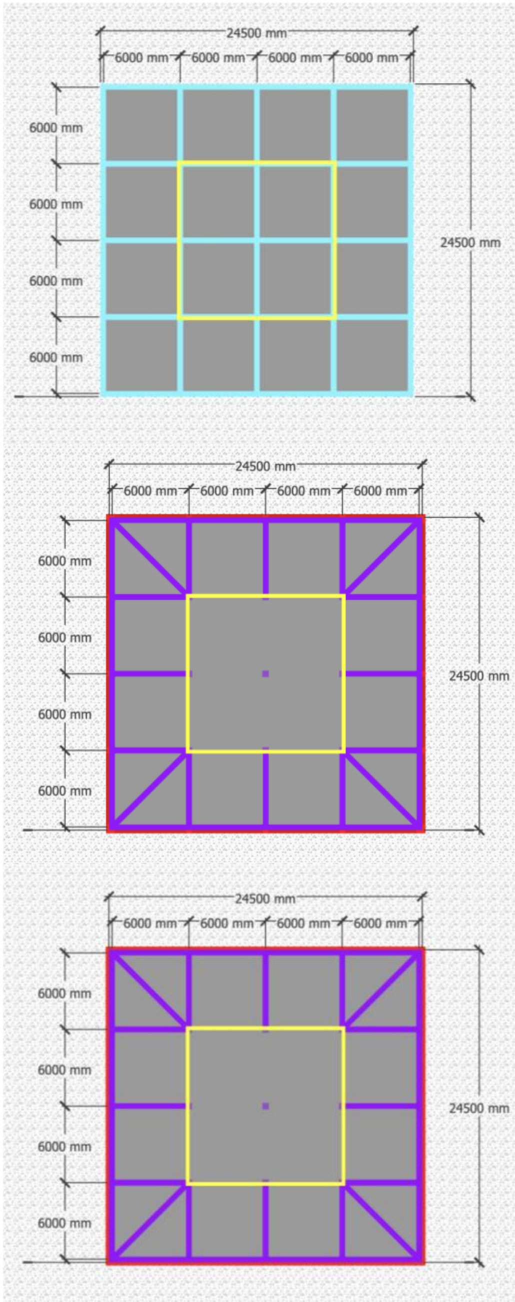


Fig. 2. Floor layout showing beam arrangement of model 1, model 2 and model 3.

All structures have a vertical support system made of RC core with 300 mm thick shear walls. The gravity system of a standard RC structure (a) consists of a 200 mm thick composite reinforced concrete slab, a 500 × 500 mm square RC column and a 450 × 600 mm RC beam. Whereas steel struts were used for diagrid exoskeleton structures. The ceiling was simulated with shell components and the diagrid parts represented with pipe elements. Lateral resistance in overturning flexure and shear is provided by the steel diagonal braces. All beams in slabs are bolted at both ends as they are designed to take gravity loads only. All models were subjected to seismic loading in the x and y directions. The dimensions and specifications of the modelled structures are presented in Table I and Table II.

TABLE I. PROPERTIES OF STRUCTURAL ELEMENTS

Member properties	Section sizes (mm)
Column	500 × 500
Beam	450 × 600
Slab	200
RC core with shear wall	300
Diagrid	355/12.5

TABLE II. PROPERTIES OF STRUCTURE

1	Details of the building
Structure	OMRF
No. of floors	G + 16
Type of building	Regular and symmetrical
Plan area	24.5 m × 24.5 m
Height of the building	65 m
Floor height:	
Ground floor	7.4 m
Typical floor	3.6 m
Support	Fixed
2	**Material properties**
Grade of concrete	C40
Grade of steel	Q345
Density of reinforced concrete	25 kN/m^2
Young's modulus of concrete, E_C	27386127.87 kN/m^2
Young's modulus of steel, E_S	2 × 10^8 kN/m^2
3	**Seismic properties**
Seismic zone	A
Importance factor	1
Response reduction factor	5 %
Soil type	0.12
Damping ratio	0.05

C. Earthquake Properties

The selection and size of earthquake data is one of the fundamental stages in constructing seismic response and fragility curves based on time history research. The selection of the records should consider a variety of factors including the type of fault, the soil conditions, the distance from the source of the earthquake, the frequency content of the record, etc. In addition, the number of records selected should be chosen so that the average of the findings of the time history analysis and variations in response from record to record are reduced to a minimum.

To study the responses of the structures, three FEMA P-695 earthquake records were used in this study. The use of several data sets enables statistical comparisons and evaluations. Figs. 3–5 show acceleration, velocity, and displacement plots in the time domain of the recordings. Data for soil type A comes from extensive occurrences made available for research in the PEER database.

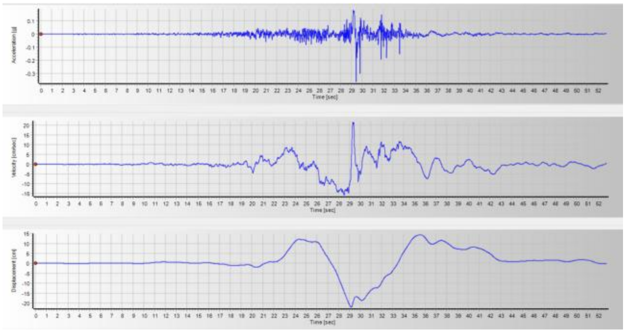


Fig. 3. Acceleration, velocity and displacement plots in the domain–Chi-Chi Earthquake.

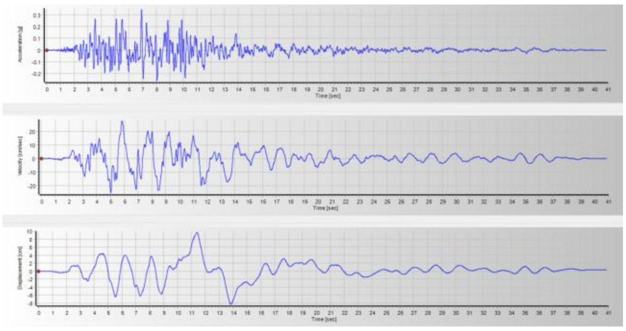


Fig. 4. Acceleration, velocity and displacement plots in the domain–Kobe Earthquake.

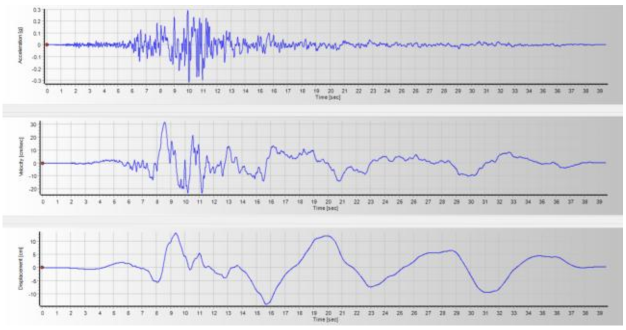


Fig. 5. Acceleration, velocity and displacement plots in the domain–Imperial Valley Earthquake.

D. Chi-Chi Earthquake

The earthquake occurred on September 21, 1999. It had a modified Mercalli intensity scale of X and a moment magnitude of 7.7. The earthquake produced intense shaking for about 30 seconds. In general, ground movements east of the fault zone and near the fault track were much stronger than west of the fault. The epicentre of the earthquake was 150 kilometres away, 150 km south of Taipei, Taiwan. The earthquake caused $10 billion in total damage resulting in 2,415 fatalities, 29 missing people, 11,305 serious injuries, 51,711 buildings destroyed, 53,768 buildings severely damaged, and 51,711 buildings destroyed. It is the second deadliest earthquake in Taiwan's history, after the Shinchiku-Taich earthquake in 1935. The summarised data are listed in Tables III and IV.

E. Kobe Earthquake

On January 17, 1995, an earthquake struck Hygo Prefecture in southern Japan, including the Hanshin area. On the Modified Mercalli Intensity Scale, it received an XI rating and a moment magnitude of 6.9. The shaking lasted about twenty seconds. The earthquake's epicentre was 20 kilometres outside of downtown Kobes, 17 kilometres below its center on the north end of Awaji Island. This earthquake claimed around 6,434 lives, 4,600 of whom were Kobe residents. With a population of 1.5 million, Kobe was the largest city closest to the epicentre and experienced the largest tremors. After the great Kant earthquake in 1923, which killed more than 105,000 people, this earthquake was the worst to hit Japan in the 20th century. Tables III and IV contain a list of the compiled data

F. Imperial Valley Earthquake

On May 18, 1940, an earthquake struck the Imperial Valley of southern California near the international border between the United States and Mexico. On the Mercalli intensity scale, it had a maximum perceived intensity of X (extreme) and a moment magnitude of 6.9. It was the first significant earthquake detected by a strong motion seismograph near a fault fracture. According to experts, the earthquake was a typical, moderately severe damage event with complicated energy release characteristics. Nine people died because of the worst earthquake in the Imperial Valleys, which also severely damaged irrigation infrastructure. The compiled data are listed in Tables III and IV.

TABLE III. GENERAL INFORMATION ABOUT THE SELECTED GROUND MOTION

Name	Magnitude	Year	Country
Chi-Chi	7.7	1999	China
Kobe	6.9	1995	Japan
Imperial Valley	6.9	1940	USA

III. SIMULATION

A. Analysis Methodology

The nonlinear finite element analysis of the model is divided into different phases. For the design verification, the structures are subjected to a linear static calculation of the gravitational load in the first step. In the second stage, the FEM is subjected to a response spectrum test with the aim of comparing its performance under earthquakes. Floor displacement relative to ground, inter-story displacements, and floor shear forces in the horizontal direction, including base shear, peak floor shear, and core shear, are monitored response quantities in seismic analysis. They serve as engineering requirement parameters on which the structural integrity and serviceability from the seismic protection perspective is based. The inelastic seismic performance of structures is then estimated using a nonlinear static analysis technique known as pushover analysis, which allows structural safety to be determined. The maximum response variable of structures, such as the global damage index, is then derived after running NLDA on a particular acceleration graph giving the time historical response of structures. Using the mode superposition approach, the Peak Floor Acceleration (PFA) at different floors is determined. PFA could be helpful in the immediate aftermath of an earthquake to potentially maximise recovery efforts, particularly in situations of undetectable damage that can be catastrophic to key lifelines.

TABLE IV. INTENSITY PARAMETERS OF SEISMIC LOAD

Parameter	Chi-Chi Earthquake	Kobe Earthquake	Imperial Valley Earthquake
Max. acceleration (g)	0.36100	0.34470	0.31520
Sustained Max. acceleration (g)	0.19000	0.26640	0.27170
Effective design acceleration (g)	0.31016	0.33735	0.32196
Predominant period (sec)	0.06000	0.16000	0.14000
Vmax/Amax: (sec)	0.06084	0.08185	0.10186
Arias intensity: (m/sec)	0.37522	1.68744	1.26460
Bracketed duration (sec)	19.87000	33.84000	29.67000
Significant duration (sec)	11.78000	12.86000	8.92000

B. Monitored Parameters

Response parameters that are monitored are as follows:

(1) Vibration characteristics

(2) Floor shear forces (horizontal direction)

(3) Floor displacement relative to ground (x, y direction)

(4) Inter-storey drift (IDR)

From a seismic protection perspective, monitored parameters are the engineering requirement variables that affect structural integrity and serviceability. The vibration characteristics correspond to the natural period of the building, the building mode shapes, and the crowd participation in each mode. To evaluate the outcome of the building's seismic performance under lateral loads, these properties can be used to provide information about the building's behaviour in the dynamic analysis. Floor shear forces in the horizontal direction include base shear and peak floor shear force. The middle of the structures serves as a starting point for measuring the floor displacement. We record peaks of positive and negative ground displacement of each floor relative to the ground in the x and y directions. IDR is calculated considering response history, IDR envelope response and geometric mean of envelope responses considering seismic loading.

C. Research Significance

There is a need for better anti-seismic measures as earthquakes pose a threat to public safety. The system can improve its economic and environmental effectiveness by updating its structure to meet current sustainable needs. This study investigates the seismic performance of exoskeleton structures and their ability to dampen earthquake-induced vibrations, considering a module set and an element sizing method. This methodology considers the influence of the diagonal angle on the behaviour of the diagrid system under seismic loading. The goal is to understand how rigid coupling affects the dynamic response of the structure and whether it can be used to achieve vibration control goals. Dynamic coupling is a big factor in how well the exoskeleton holds up. The exoskeleton is modelled as a dynamic system that can be modified to optimise its mass, stiffness, and damping properties. The construction approach of the Diagrid exoskeleton can be used not only to construct new buildings, but also to restore existing structures and improve their seismic resilience.

D. Advantages and Limitations of Diagrid Structures

In modern structural engineering, the diagrid idea has emerged as a viable option. There are several benefits to using a diagrid design, some of which are included in the list below:

(1) Compared to braced frame structures, the use of diagonal grids leads to a reduction in steel consumption of about 1/5.
(2) A moment frame skyscraper cannot transfer weight as well as a diagrid structure. In this type of structural system, the perimeter columns are replaced by a system of triangular diagonal girders and horizontal rings.
(3) The structures are visually striking and make full use of the building materials.
(4) The diagrid exoskeleton structure enables engineers to design safer taller buildings.
(5) Due to the diagonal elements, lateral loads are efficiently resisted, allowing the freedom to design core columns against gravity loads only.
(6) Improved rigidity and durability since diagonals are trusses.
(7) The construction of strong shear cores is not necessary in the presence of large shear stresses, since axial actions will withstand the pressures exerted on the structures. Shear walls are not necessary on the facade or in the core.
(8) Stiffness and monolithic behaviour due to the ability of the diagonal structure to efficiently redistribute the load to the members in the event of a partial failure of an area of the building. This behaviour completely prevents the structural collapse of skyscrapers.
(9) Unique floor plans as the interiors are largely column-free.

The diagrid exoskeleton is a promising structure system that has a lot to offer. Due to its shortcomings, it's not entirely flawless, just like every other system out there. These are some of them:

(1) Due to the complicated architecture of the diagrid system, calculation and design challenges may arise.
(2) Due to design factors such as the diagonal angle and the bending-shear compliance ratio, it is not possible to predict in advance whether the requirement for bar strength or for the overall stiffness would predominate.
(3) A diagrid constructed of steel can only be 100 stories tall, while a diagrid constructed of concrete can only be 60 stories tall.
(4) The concrete diagonal structure is quite complicated. A lot of formwork is therefore required, which ultimately drives up the construction costs.
(5) Steel elements are prefabricated due to their complexity.
(6) A special internal height can be caused by an internal diagrid system.

IV. FINDINGS

A. Modal Analysis

Modal analysis is a technique for determining vibrational properties of a structure such as natural frequencies, mode shapes, and mode participation factors. It is the most basic of all types of dynamic analysis. Mode extraction is the term used to describe the computation of eigenvalues and eigenvectors.

A building is better able to withstand lateral loads, including wind and seismic loads, when it has a high natural frequency. Table V shows how seismic stress affects natural frequencies. 34 modes were considered. When a building's natural frequency is increased, the displacement caused by lateral loads is reduced. As would be predicted, as taller structures are more flexible, stiffness increases as building size decreases. The natural frequency decreases as stiffness decreases because it is defined as: $\sqrt{k/m}$, where k is the stiffness and m is the mass. Model 3 with the 2-storey module diagrid system also has the highest natural frequency. The model 2 with a four-story diagrid system has a slightly lower natural frequency than the model 3. However, the natural frequency of the model 1 is significantly lower. This can be observed from mode 10 onwards. Fig. 6 shows the results plotted on a line graph.

TABLE V. NATURAL FREQUENCIES FOR 3 MODELS

Modes	Model 1 Frequency (cycles/time)	Model 2 Frequency (cycles/time)	Model 3 Frequency (cycles/time)
1	1.07	1.3	1.36
2	1.07	1.3	1.36
4	4.59	4.5	4.68
6	6.55	5.72	6.29
8	7.47	8.89	9.23
10	7.81	9.47	10.46
12	8.79	11.28	11.72
14	9.04	12.81	13.89
16	9.89	13.34	14.09
18	10.60	13.69	14.97
20	12.11	15.92	18
22	12.58	16.46	18.2
24	13.87	17.32	18.5
26	14.94	19.44	21.84
28	15.27	21.03	22.25
30	15.40	21.92	22.48
32	15.45	22.33	23.71
34	15.66	23.43	24.1

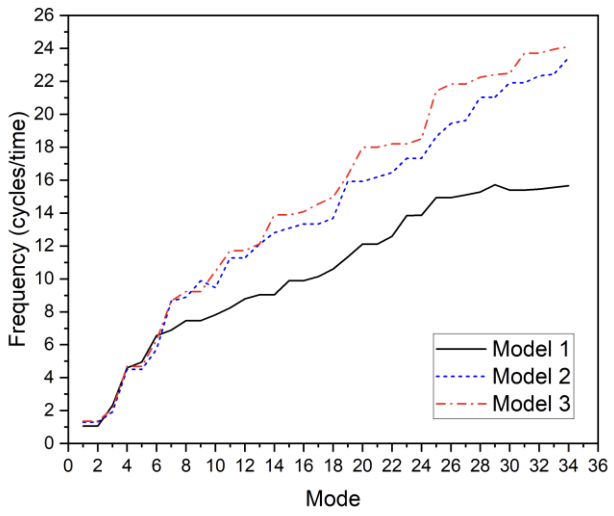


Fig. 6. Natural frequency.

B. *Mode Shape*

To describe the deformation that a structure experiences when subjected to an excitation, the concepts of mode shape and resonance are required. There is an infinite variety of resonant frequencies and mode shapes for physical structures. The stiffness force and inertial force cancel each other when an input excites a structure at a resonant frequency, resulting in a low effective mass for the structure. The theory of structural dynamics shows that each resonant frequency has an associated characteristic shape, and that resonance leads to a structural response that requires relatively little driving power. The characteristic shape of a structure is composed of the sum of the mode shapes associated with each of the resonant frequencies used to excite it. The results for mode shape analysis for each model have been illustrated below in Fig. 7, Fig. 8, and Fig. 9 respectively.

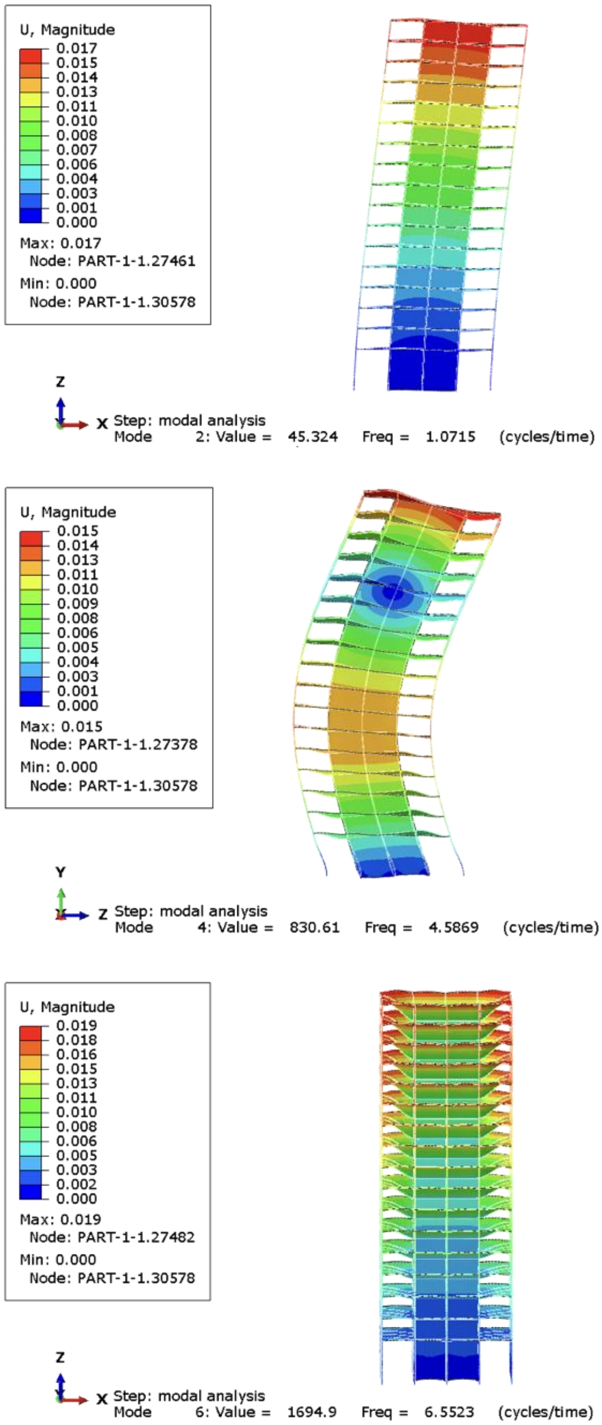


Fig. 7. Mode shape of model 1.

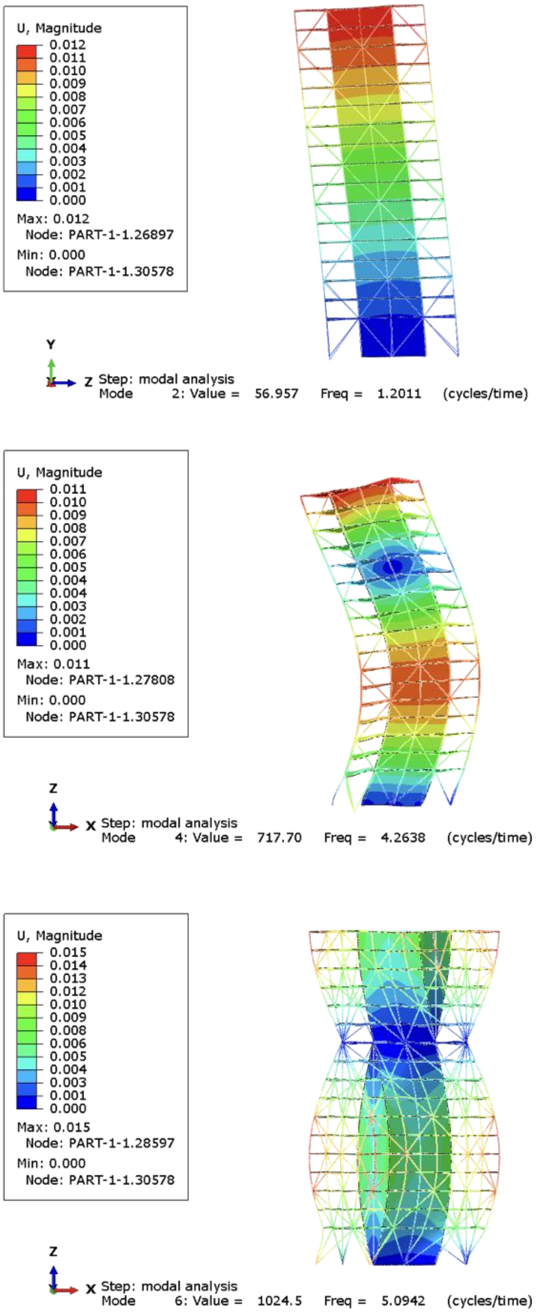
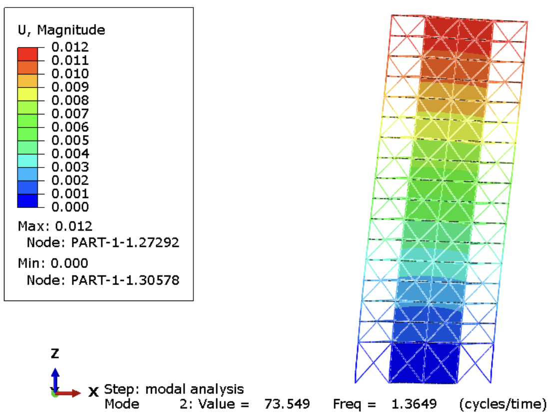


Fig. 8. Mode shape of model 2.



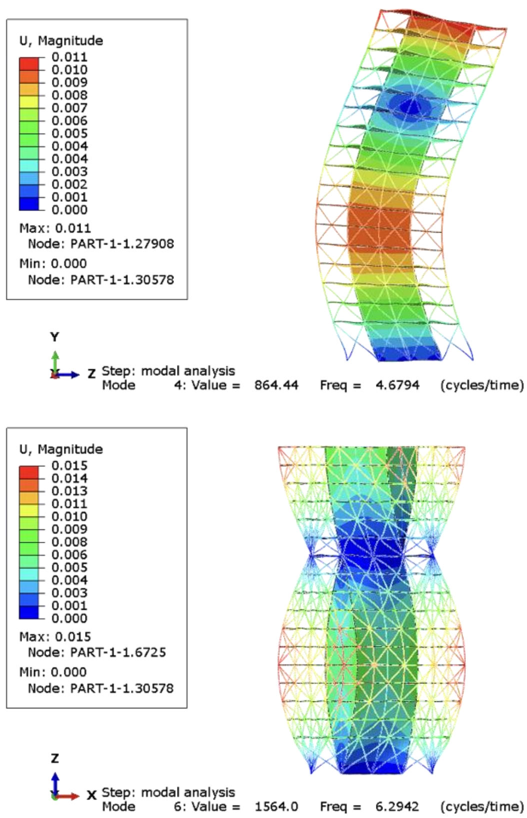


Fig. 9. Mode shape of model 3.

C. *Inter-storey Drift Ratio (IDR)*

A standard RC structure-model 1, a two-module diagrid exoskeleton-model 2 and a four-module diagrid exoskeleton-model 3, all subjected to seismic loading of PGA 0.36 g (Chi-Chi earthquakes), PGA 0.34 g (Kobe earthquake), and PGA 0.3152 g (Imperial Valley earthquake).

The results for IDR are shown in Figs. 10 and 11 for the Chi-Chi earthquake, Figs. 12 and 13 for the Kobe earthquake, and Figs. 14 and 15 for the Imperial Valley earthquake.

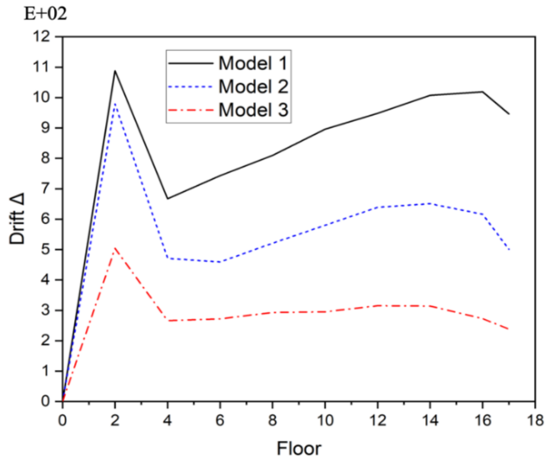


Fig. 10. Displacement in x-direction (Chi-Chi Earthquake).

When the models were subjected to a Chi-Chi earthquake, it is evident that model 3 experiences the least displacement. While model 1 experiences the greatest shift.

In the case of the Kobe earthquake, model 2 shows a higher drift in the x-direction and model 1 shows a higher drift in the y-direction. On the other hand, model 1 experiences the least drift during an earthquake in the Imperial Valley.

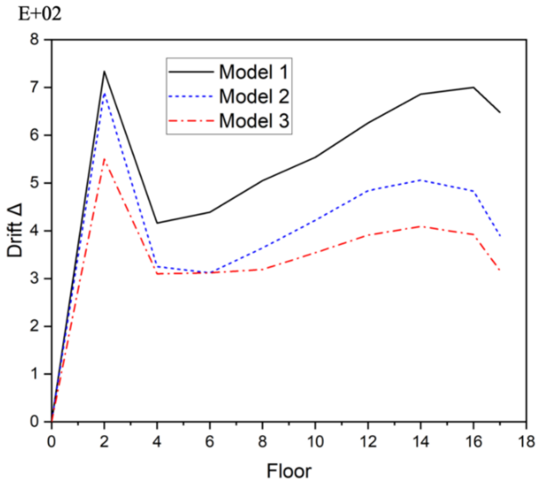


Fig. 11. Displacement in y-direction (Chi-Chi Earthquake).

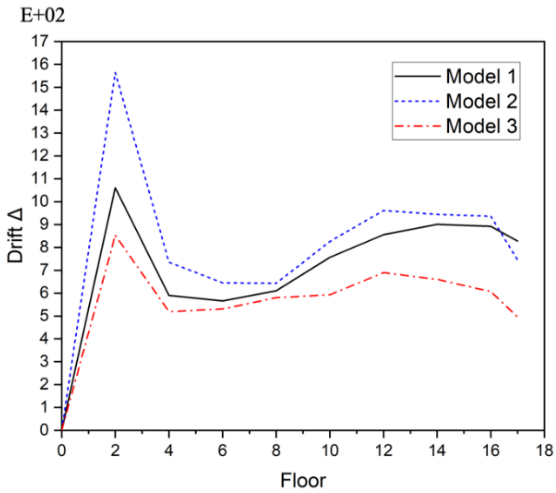


Fig. 12. Displacement in x-direction (Kobe Earthquake).

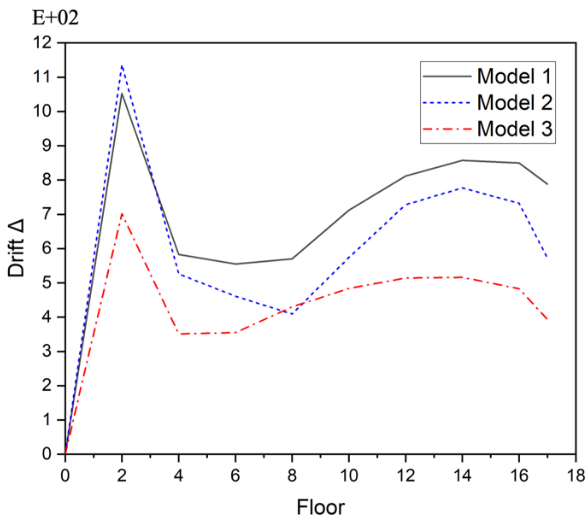


Fig. 13. Displacement in y-direction (Kobe Earthquake).

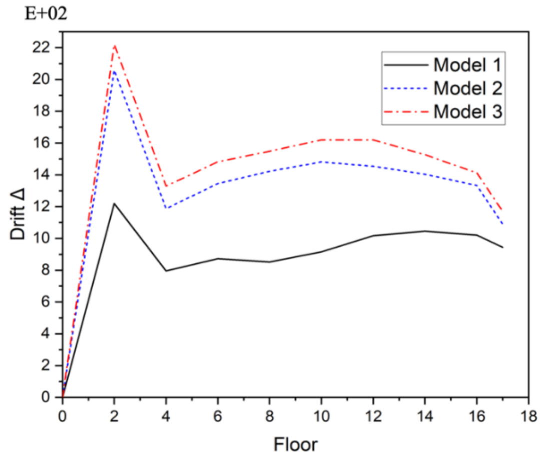


Fig. 14. Displacement in x-direction (Imperial Valley Earthquake).

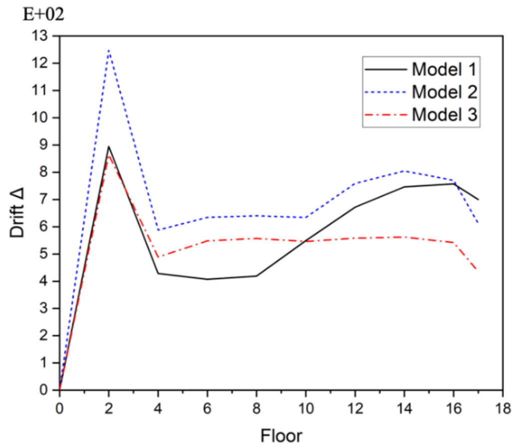


Fig. 15. Displacement in y-direction (Imperial Valley Earthquake).

V. Conclusion

This research study attempted to determine if exoskeleton diagrid structures would be a practical and efficient way to manage structural response to seismic loading. The exoskeleton diagrid structure is designed as a dynamic system with adjustable mass, stiffness, and damping. Designing a high-rise building is a long and complicated process of trying to create a structural system that both conforms to architectural constraints and can safely carry gravitational and lateral loads. In addition, to maintain occupant comfort, the designer must minimise vibration and adhere to certain lateral displacement limitations. The theory allowed the development of a dynamic system whose architecture could be adapted to the requirements of the seismic zone. Some of the observations are floor displacement is reduced while peak inter-storey drift is higher. In addition to displacement and deformation control, significant reductions in internal forces are observed in the diagrid exoskeleton structures.

Conflict of Interest

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Mariia Magsi designed the study, performed the experiment, contributed to the interpretation of the results, and took the lead in writing the manuscript; Yuye Zhang and Xinzhi Dang supervised the project and helped shape the research, analysis, and manuscript; all authors have approved the final version.

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