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Exoskeleton: Exploring the Retrofitting Solution for Seismic Upgradation of Existing Irregular Buildings

Anvesha Bhadouriya[1*], L. G. Kalurkar[2]
[1]Research Scholar, Department of Civil Engineering, Jawaharlal Nehru Engineering College, Aurangabad, India
[2]Associate Professor, Department of Civil Engineering, Jawaharlal Nehru Engineering College, Aurangabad, India

***Abstract*: Self-assembling exoskeleton structures are fundamentally a self-supporting structural system whose elements are intentionally connected to each other additionally integrated with the primary frame. The integrity with the primary frame depends upon the type of structure. Precursory studies have described enormous potentials of exoskeletons and braces. Viewing the capability and adaptability has attracted enormous considerations especially in retrofitting. This study basically deals with the study of exoskeletons & braces so as to consider it as a sole retrofitting solution.**

***Keywords*: Structural dynamics, Structural control, Exoskeleton structure, Coupling, Base motion, Frequency response.**

1. Introduction

Many structures fail due to the earthquake haphazard and cannot withstand the seismic forces. Disasters cause huge loss to life and properties. Control measures as well as resisting structures are the most necessitated according to the demand of time. Hence, there is the major need to upgrade the building structures. Even old buildings need to be strengthened to hold up the vibrations and drift. Retrofitting is one of the best options for strengthening existing structures. New structure can be designed with seismic load considerations. Severe damage is caused in seismic areas as both gravitational and lateral loads act simultaneously. Lots of stresses are developed in this condition. Shear walls are conventionally used as the solution for lateral loads. Irregularity in fundamental time period, internal drifts, lateral displacements and responses of structures are the core studies in seismic stiffness of building. Canterbury and Chile earthquakes in 2010 and Tohoku earthquake in 2011 are the recent examples of the severe damages caused to the structure under haphazard. Not only is the building endangered but also the inhabitants living in it. The conventional techniques were not efficiently reliable, and the risk of damage is paramountly hiked. As the current demand, the increasing population and development emerge the ideas of taller buildings. Taller buildings are the flexible type of structures. As the height of building increases, intensity of wind load also increases. It is very important to analyze dynamic loads while the designing of high – rise buildings. It is very important to find the appropriate proportion between the height of structure and its width for the designing process. Vulnerability of the structure increases for the tall buildings under dynamic lateral loads like earthquake loads and wind loads. The minimum of displacement or the fundamental period can cause the large amount of loss to generation. Different materials show different responses due to their varying strengths. Selection of material plays a vital role in the resistance to the loads and stresses induced. Physical properties of materials determine the capacity of structure. Steel show better result than RCC structures in the parametric studies in research. Now-a-days, availability of technologies and software has made it possible to have a thorough analysis of structures and carry out a most efficient design to resist maximum dynamic loading and the stresses developed therein. The global development is being undertaken with an appreciable speed. There is a 10 | P a g e international competition for the tallest building in all the countries. This race is leading in the constant increase of the height and apparently increasing the risks and threats to the structure. Exoskeleton, diagrid and bracings are some of the innovative techniques suggested in the papers by researchers. These structures can withstand the seismic and wind loads to a larger extent. Various studies and comparative analysis are carried out in order to get the efficiency of these structures. Fundamental time period, story displacement, internal story drift, strength, etc. are some parameters compared with the conventional building. Positive results are seen on the application of the new techniques. Internal displacements are considerably reduced and the capacity of the structure to hold on seismic thrusts increases. It reduces the heavy damages and thereby creates an economic solution to reduce the expensive maintenance costs. Also, these structures give an aesthetically good look and elevation for a

*Corresponding author: bhadouriya.anvesha26@gmail.com

building. Twists are avoided by the presence of these external elements. Reliability of the structure is increased predominantly. The basic structure is strengthened with the minimum low-cost techniques. Life of building is considerably increased which helps in avoiding the repetitive remunerations of structure. Also, the disaster stress is decreased. These systems affect the building performance in direct or indirect manner. Studies state that the overall performance of the building is enhanced, and the efficient possible solutions are introduced. Here are some figures showing the disastrous effects on the structures

2. Precursory Studies

A. Literature Survey

The above section has enlightened the theme of the research area. Under this section the precursory researches carried by dominant researchers were studied and elaborated so as to find a research gap on the basis of which further study was proceeded.

M. A. Youssef Et Al. [1] have observed that the lateral load resisting system beneficially used is steel bracing. There are various studies and guidelines available on the topic, still the researchers think it isn't sufficient and carried out experiment on two RC frames. The first frame was a moment frame and the other was braced frame. The braced frame was rationally designed including the building connections. The applied seismic loads on both the frames according to the seismic codes available. A detailed report was made for both the frames and the results were compared. After the comparison, it was found that the braced frame acted more effectively than the Moment frame in many parameters like ductility, strength, capacity to withstand seismic loads, etc. The experimental procedure adopted above gives the precise and practical responses of the structure. The lack of designing methods for such frames is creating obstacle in the development if such frames. Hence, this work introduces the design methodology and can be the initiative in the upcoming research

Kelly Young Et Al. [2] have investigated Eccentrically Braced Frames (EBF) with irregularities for its fundamental time period. Here, fundamental time period means the period of vibration of structure under seismic loads. Design and analysis of 12 EBFs are carried out. Comprehensive parametric study and the computer-based stimulations are considered for the work. Equations were developed based on the vibration theory for the fundamental time period. Geometric vertical and horizontal irregularities are considered for the analysis. Fundamental period for all EBFs classifies by the heights using ACSE equations, Adeli-equations, Rayleigh's equations and ETABS data is collectively used for the comparison. After the comparison it was found that the three variable model responsible for irregularities can be suitable for the Rayleigh data. This model is more relevant that the equations considering height solely. The developed equations are confirmed by comparing the EBFs data. Design and analysis can be speed up for the engineers using these equations by considering the geometric irregularities. It was aimed to introduce the simple equations for the quick and precise estimation of fundamental period.

Wenwu Lan Et Al. [3] have proposed the detailed study of steel-concrete composite structure experimentally and analytically. Four samples of wall at full-scale applying the cyclic load for the reversal patterns are tested in experimental study. Load deformation responses and the cracking patterns of the wall specimens are recorded and explained. But it wasn't enough to get the complete analysis due to the complex structures of shear walls and the diagonal bracings. Effect of various parameters was not explained in experimental work. Hence, FE methods using DIANA were used to analyze the work. Experimental results were confirmed by FE models and fruitful results were found. Shear span ratio, axial load, the size, and thickness of elements were some parameters that affected the seismic responses of the structure. X-shaped bracing effectively affected the shear capacity was observed in experimental method. Analytical method showed that the use of flat plates along with X-bracing withstands more shear force and are more beneficial.

Giovanni Maria Montouri Et Al. [4] have assessed the "local" structural issue in the deigning method of diagrid high rise building for a framework of 90 story building. The method for introducing the Secondary Bracing Systems (SBS) as a function of geometry of diagrid was proposed. The pattern is applied on the perimeter of the sample with different stimulations and heights at diagonal. The sample is analyzed for both with and without SBS for a diagrid system at a tall building. The simple procedure to analyze and design the SBS elements is proposed. The local questions were discussed in accordance with the accuracy, stability and safety. It showed that internal columns face the stability issue and can face buckling. Local flexibility and the internal drift are also some local issues. Introduction of SBS at the central core portion of building can eliminate the flexural complexity and increases the weight of structure by 3%. Also, local problems of buckling, internal drift, etc. are solved at a satisfactory extent. The structures with SBS overcame the structures without SBS in every aspect and local problems. The approach for the study was simplified and easy.

L. Martelli Et Al. [5] have explained the performance of the existing structure under seismic loads with the installation of exoskeleton. Exoskeleton is the external steel element which absorbs the seismic loads in order to increase the building performance. The performance of developed couple system under seismic action was studied with the application of exoskeleton. The external structure is connected by a non-dissipative rigid link to the primary building. The seismic responses of the building were checked according to frequencies, period of vibrations, shear force, displacements and stiffness. Two models were made, viz., existing structure and existing structure with retrofitting, and compared the responses. Study with varying mass ratios resulted that the coupled system had more frequencies due to increase in total weight and stiffness. Increased stiffness causes the increase in acceleration and reduces the period of vibration. The study concluded that the appreciable amount of shear forces in the primary building are taken by the exoskeleton. Floor displacements are reduced and cost of operations is low.

Anna Reggio Et Al. [6] have stated that the external self-supporting structural system, which is also called as Biomimetic Exoskeleton structures, are connected to the main structure in order to protect or strengthen it. In this study, the performance of building under seismic loading is studied. An exoskeleton system is designed with the dynamic properties of mass, stiffness and damping. The main aim is to control the response of inner structure. The parametric study of frequency responses under displacement and acceleration responses and transmitted forces is carried out. The non-dimensional form of dynamic equilibrium is set and harmonic base motion response for increasing parameters is analyzed. A seismic response for a coupled mid-rise RC frame of non-ductile behavior and an exoskeleton of steel diagrid-like lattice structure. The work concludes that the displacements and deformations are controlled significantly and the internal shear forces acting at base and floor are reduced.

Table 1
Development of Models

Designation of Model	Description
BFM	Bare Frame Model
CES	Chevron Exoskeleton Frame
XES	X Exoskeleton Frame

Table 2
Material Properties

1.	Grade of concrete	M30
2.	Grade of reinforcing steel	Fe 415
3.	Density of concrete	25 KN/m3
4.	Density of brick masonry	19 KN/m3
5.	Damping ratio	5%

Table 3
Geometrical Properties

1.	Plan Dimensions	52m X 52m
2.	Height of the structure	62.7 m
3.	Height of storeys	3 m
4.	Thickness of Slabs	150 mm
5.	Internal Wall thickness	150 mm
6.	External wall thickness	150 mm

Table 4
Geometrical Properties

1.	Floor load	3.75 KN/m2
2.	Live load	3.0 KN/m2
3.	Wall load	15 KN/m
4.	Code for RCC	IS 456 (2000)
5.	Seismic code	IS 1893 (2016)
6.	Zone	IV (severe)
7.	Importance factor	1.2
8.	Frame type	SMRF
9.	Response reduction factor	5.0
10.	Site soil type	Medium (II)

B. *Precursory Studies*

For comparative parametric study, this study was carried out on the basis of models simulated using CSI's ETABS 2019. The structure considered for the study was an L-shaped irregular building which was a 20 Storied building. The geometric and structural specifications of the models simulated are defined in the subsequent part of this article. The general and structural properties which were considered for the simulation of models have been specified below:

Table 5
Structural Properties

1.	Type of sections	R.C.C Framed with Exoskeletons
2.	Columns (C1)	450 X 900
3.	Columns (C2)	450 X 1200
4.	Beams (B1)	300 X 600
5.	Beams (B2)	300 X 750

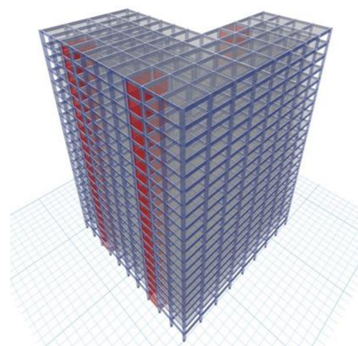

Fig. 1. Maximum Drift (X)

3. Results and Discussion

A. *Maximum Drift*

Story drift is the displacement of story of a structure that takes place because of lateral forces, when acts on the structure. In this study the maximum drift is observed for both X and Y directions and compare with all models.

1) *Maximum Story drift inX-Direction*

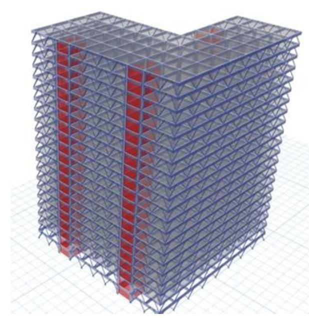

Fig. 2. Extruded View of CES

Observationsoftheresultsshowsthatthemaximumdriftoccurre dforbareframestructure, on the other hand the maximum drift was decreased in case of different bracing system and exo skeleton system. As per the observations of the results it is found that the maximum drift is reduced to 29% and 18% for Xexo skeleton and chevron exoskeleton frame structures respectively in X-Direction. In case of exoskeleton structures, it is assumed that the peripheral columns are failed due to the action of lateral forces. Hence, it can be truly said that the X exoskeleton structure behaves good and has shown good results.

Maximum Drift (mm) in X-Direction		
Bare Frame	XES	CES
7.62	5.40	6.26

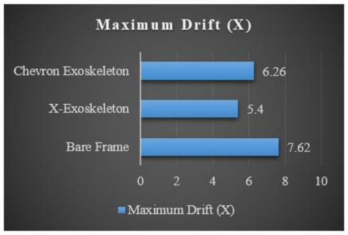

Fig. 3. Maximum Drift (X)

2) As per the Maximum Story drift in Y-Direction

Here, the maximum drift values in Y-Direction have been elaborated. As per the observations of the results it is found that the maximum drift is reduced to52% and 35% for X exoskeleton and chevron exoskeleton frame structures respectively in Y-Direction. In case of exoskeleton structures, it is assumed that the peripheral columnsare failed due to the action of lateral forces. Considering this condition, it is found that the X exoskeleton structure behaves good and shown good results. So, we can say that the exo- skeleton structures have good capacity against lateralforces.

Maximum Drift (mm) in Y-Direction		
Bare Frame	XES	CES
12.70	6.07	8.24

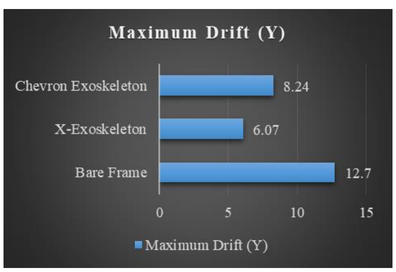

Fig. 4. Maximum Drift (Y)

B. *Fundamental Time Period*

Time period is the amount of time required for a structure to complete one mode of oscillation under the action of lateral loads. As the time period of the structure increases the base shear of the structure is less. In this study the maximum time-period is observed in bare frame model. And the minimum time-period is observed in Chevron Exoskeleton model. The time-period of bare frame is maximum and for exoskeleton is reduced to 27% and 18% for X exoskeleton and Chevron exoskeleton frame respectively.

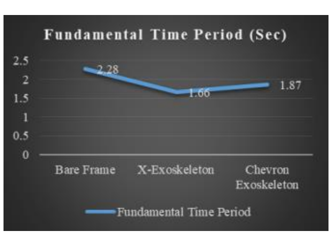

Fig. 5. Fundamental time period

Fundamental Time Period (sec)		
Bare Frame	XES	CES
2.28	1.66	1.87

C. *Frequency*

Frequency is the term that refers to the number of oscillation cycles per unit time. It shows the nature of earthquake and its strength about its effect. Frequency is inversely proportional to the time period. In this study we have compared the frequency of different models i.e., X and Chevron Exoskeleton Structures with each other to show the comparison of the frequency between each other.

Frequency (cyc/sec)		
Bare Frame	XES	CES
13.66	11.35	11.37

D. *Stiffness*

Stiffness is the term that refers to the ability of the structure that provides the strength against the deformation and the displacement against lateral loadings. In high rise structures stiffness provides the important role to maintain the strength of the structure against lateral loading. In this study the maximum stiffness of all 5 models is compared to each other. The maximum stiffness of all 3 models for X and Y directions are given in below tables.

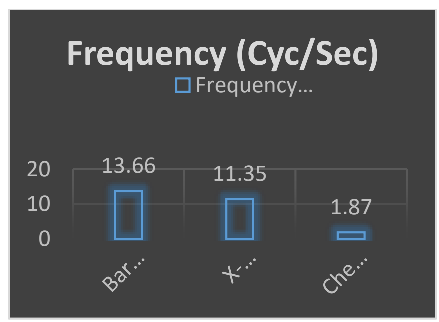

Fig. 6. Frequency

Stiffness in X (kN/m)		
Bare Frame	XES	CES
3432447	27390354	35447893

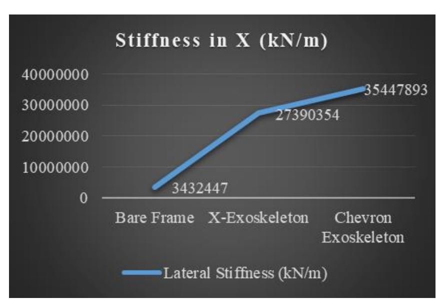

Fig. 7. Stiffness in X

Stiffness in Y (kN/m)		
Bare Frame	XES	CES
19438960	20637006	26922084

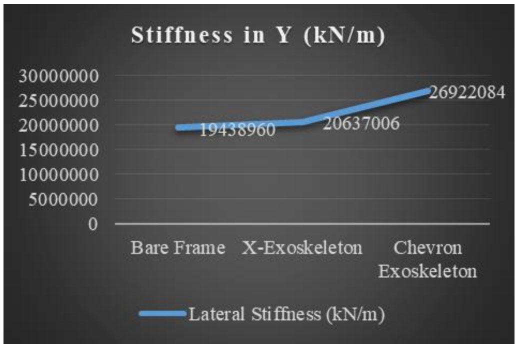

Fig. 8. Stiffness in Y

E. Base Shear

Base Reaction is the amount of force that occurs at the base of the structure due to the action oflateralforce.Inthisstudywehavecomparedthedifferentfamemodelwitheachother.Total five models have compared each other in terms of Base reaction in a structure. According to IS 1893 part 1 the base reaction for dynamic analysis should be equal to or greater than the base reaction of static analysis, if this criterion is not satisfied then the ratio of base shear of static and dynamic analysis should be multiplied with the base shear of dynamic analysis and it should be increase. In this study the criteria are satisfied as stated above and the base shear isincreased.ThebaseshearobtainedfromtheanalysisforXandYDirectionsaregivenbelow.

Base Shear in X (kN)		
Bare Frame	XES	CES
65809.34	69019.34	64568.84

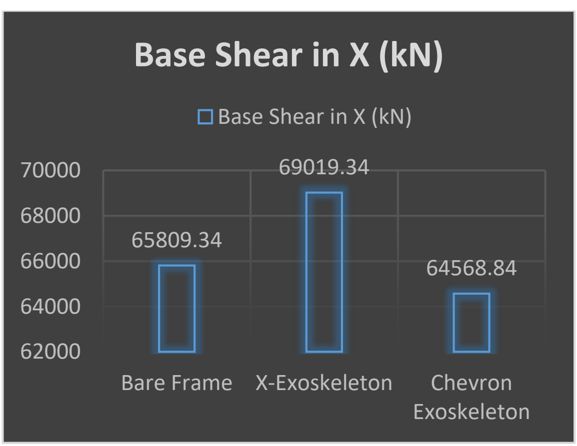

Fig. 9. Base shear in Y

Base Shear in Y (kN)		
Bare Frame	XES	CES
65801.37	64893.72	65413.37

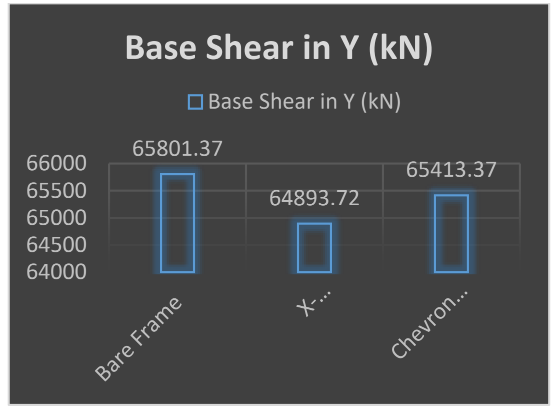

Fig. 10. Base shear in Y

4. Conclusion

1. In both the directions the drift values indicate very impressive results in exoskeleton structures even after the progressive failure of peripheral columns.
2. The Time period values also indicates very good result, though the columns have undergone progressive collapse.
3. Chevron Exoskeletons shows a controlled frequency level of vibrations.
4. The maximum base shear is observed for the X exoskeleton structure and minimum for Chevron exoskeleton structure.

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