Analysis and Design of Conjoined Tall buildings

Mit R. Patel, Paresh V. Patel

Abstract—The current situation of rapid urbanization, rising land prices, and diminishing agricultural land are increasing the need for multi-storey buildings. The structural system of multi-storey buildings is governed by the stiffness along with strength due to significant effect of lateral loads due to earthquake and wind. A variety of structural systems for tall buildings like wall-frame, tubular, outrigger-belt truss, diagrid structures, have been developed for resisting lateral loads. Connecting two or more individual buildings at different levels along the height has created a new structural system, known as conjoined building. Due to increased lateral stiffness conjoined building is an efficient alternative structural system for tall buildings. Present study focuses on analysis and design of conjoined tall buildings. The individual wall-frame building considered for the current study has a plan size of 30 m × 30 m and different number of storey as 30, 40, 50, and 60. Conjoined buildings are created by connecting four individual buildings at the top. Four individual buildings are arranged in two rows with two buildings in each row. The clear spacing between the buildings is 20 m. Seismic and wind forces are considered according to IS 1893 (Part 1):2016 and IS 875(Part 3):2015 respectively. Interference effect is considered to evaluate dynamic wind load on conjoined buildings. To model and analyse structures, ETABS software is used. For both the individual and conjoined buildings, analysis results are compared in terms of natural time period, base shear, lateral displacement and inter-story drift. For both the type of buildings sizes of structural elements along with governing load cases are presented. The results of the present study demonstrate that as building height increases, a conjoined structural system becomes more effective at resisting lateral forces.

Index Terms**—Tall building, Conjoined structure, Analysis, Design.**

I. INTRODUCTION

THE increasing global population and rapid urbanization have necessitated the exploration of vertical growth and the efficient utilization of limited land resources. Tall buildings have become an acceptable solution to this urban demand, offering a unique blend of functionality, aesthetics, and engineering prowess. Due to development in innovative structural systems, construction technology, building services and computational methods, tall, supertall, and megatall buildings became more common during past few decades.

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With the advancement in technologies, many interior and exterior structural systems developed to resist the lateral load on a tall building. A conjoined structural system is one of the exterior structural systems for a tall building. The term conjoined describes the joining of two or more individual towers to form one bigger building [1].

The major function of a structural system is to stabilize the overturning moment developed due to lateral loads. To increase lateral load resistance satisfying serviceability requirements, structural elements' dimensions need to be increased, which may increase the self-weight of the structure and consumption of materials. By joining two or more buildings with a link structure forming a conjoined structure that transfers internal forces, the magnitudes of the moments in the two frames can be reduced [2]. A small axial force in structural members of individual buildings can result in greater moments of resistance because of the large lever arm involved, which lowers tensile forces in columns [3]. At present, few conjoined buildings are constructed, but their number will increase in the future. Some of the examples of conjoined buildings are Petronas tower at Kuala Lumpur, Incheon Tower at South Korea, Marina Bay Sand building at Singapore. The conjoined structural system is a feasible alternative to increase the lateral stiffness and stability of structures [4]. Several advantages come with this design approach, such as improved design flexibility, improved performance under heavy lateral loads, and increased stability [5]. Moon presented a comprehensive exploration of tall buildings, encompassing their architectural design, structural engineering, and impact on the urban environment [5].

Increased lateral stiffness of conjoined building can be effective in controlling lateral displacement and inter-storey drift of tall buildings without increase in sizes of structural elements. So, joining individual structures to form conjoined building will be cost effective, if the height of building is higher. Height criteria for adopting conjoined building and comparison of analysis and design results in Indian context are not available in literature.

This study presents analysis and design of the conjoined structures developed by joining four individual building having wall-frame structural system. For modelling, analysis and design of conjoined buildings ETABS software is used. Seismic forces and wind forces are estimated and applied on the structures as per IS 1893(Part 1) : 2016 and IS 875(Part 3) : 2015 respectively. Interference effect is considered to evaluate dynamic wind forces on conjoined buildings. Structural responses of individual and conjoined buildings are compared and presented in the paper.

II. Building Configuration

The individual 30, 40, 50, and 60-storey building is having 30 m × 30 m plan dimensions as shown in Fig. 1a. Each building is having 3.6 m storey height. Four individual buildings with a 20 m spacing are joined together by a link structure at the top to form a conjoined building. There are two buildings in each row of the four isolated buildings. Fig. 1b, depict the typical floor plan of a conjoined building with a link structure connecting four separate individual buildings. The number of storey in the link structure is assumed to be 1/10 of number of stories of the individual buildings. Steel braces are provided in the link structure.

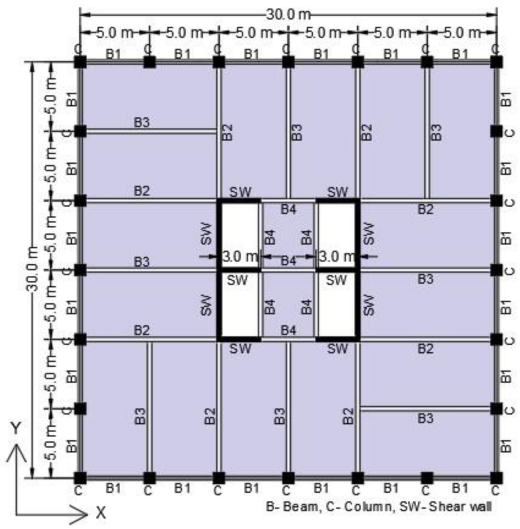

Fig. 1(a). Typical floor plan of Individual buildings.

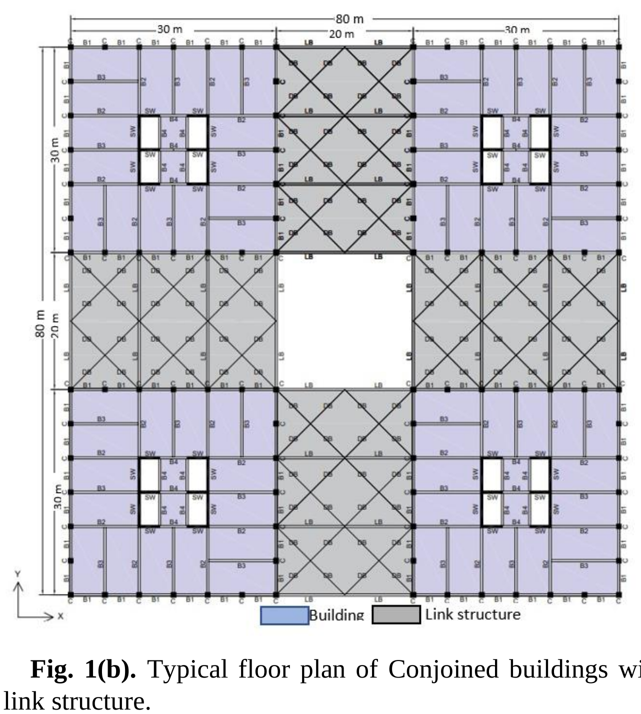

Fig. 1(b). Typical floor plan of Conjoined buildings with link structure.

III. Loading Data

According to IS 875 (Part 1): 1987 [6] and IS 875 (Part 2): 1987 [7], respectively, dead load (DL) and imposed load (LL) are considered for individual and conjoined buildings.

Gravity load of buildings includes:

- Self-weight of structural members
- Dead load of slab = 3.125 kN/m^2
- Wall load at periphery beams = 4 kN/m
- Floor finish = 1.5 kN/m^2
- Live load on slab = 4 kN/m^2

All buildings are located in seismic zone III. Equivalent static analysis and dynamic response spectrum analysis for seismic loads are carried out as per IS 1893 (Part 1): 2016 [8] using ETABS software. Table I. shows parameters considered for estimating seismic forces for all the buildings.

TABLE I
SEISMIC LOAD DATA

Location	Ahmedabad
Seismic zone	III
Zone factor	0.16
Importance factor (I)	1.2
Response reduction factor	5
Soil type	Medium
Time Period	As per IS 1893 (Part 1):2016

Static and dynamic methods are used to estimate wind loads on buildings. Dynamic wind loading in along and across direction are evaluated using the gust factor method described in IS 875 (Part 3):2015 [9]. Table II lists the parameters taken into account while evaluating the wind load on individual buildings with 30, 40, 50, and 60 storey.

Wind loading on conjoined buildings include buildings on which wind act first, known as interfering building, and buildings on which wind act subsequently, known as Principal building. Interference wind effect due to closely spaced building is considered for conjoined buildings. The ratio of wind load on the interfering building and principal building is 10: -4 [10]. When four individual buildings connected by link structure at the top, wind load at that height is calculated as individual building. As the structural elements of individual and conjoined buildings are made of steel-concrete composite, load combinations are considered as per IS 800:2007 [11] for the analysis and design of buildings.

TABLE II
WIND LOAD DATA

Location	Ahmedabad
Basic Wind Speed Vb (m/s)	39
Terrain Category	2
Risk Coefficient k_1	1
Topography Factor k_3	1
Importance Factor for cyclonic region k_4	1

IV. MODELING OF TALL BUILDING

Modeling of individual and conjoined structures using ETABS software is discussed in this section. The following are the steps for modeling and analysis of structure:

- Define the geometry of structure, sectional and material properties of the structural elements.
- Make a three-dimensional structural model of the building using a typical floor plan and elevation of the structural elements.
- Add the support conditions to the 3D model.
- Define and assign the loads to the building as per section V. Also, load combinations are defined.
- Analyse the Model.
- Based on the results of the analysis, structural components are designed, and if necessary, sections are changed and the analysis is repeated, till the strength and serviceability criteria are satisfied.

Fig. 2 presents the nomenclature of building models considered for the present study. It includes single / conjoined buildings (S or C), total number of storeys, cause of lateral load, direction (X or Y) of lateral load.

V. DESIGN SECTION

For the analysis of all building models, materials of M40 grade concrete, structural steel of Fe345 grade, and reinforcement of HYSD 500D grade are used. The RCC slab of a thickness of 125mm and supporting structural steel members are considered. Table III presents the design sections and governing load case for main vertical structural elements like concrete-filled steel tubular columns and shear walls.

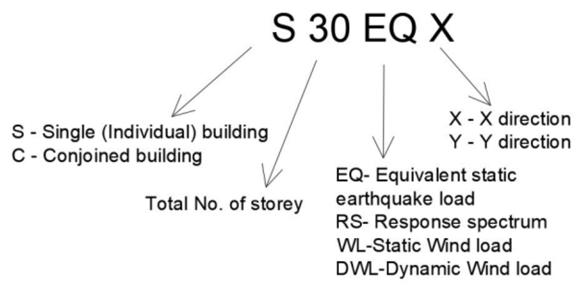

Fig. 2. Nomenclature of building models

Based on comparison of design section of structural members of individual and conjoined buildings, it is found that the shear wall sizes in conjoined buildings are 133%, 115%, 86%, and 85% as compared to individual buildings with 30, 40, 50, and 60 storey respectively. Similar trends is also observed for in the sizes of the beam and columns.

It is also observed that wind load governs the design of individual buildings, whereas earthquake load governs the design of conjoined buildings.

TABLE III

DESIGN SECTION AND GOVERNING LOAD CASES OF COLUMN AND SHEAR WALL

Building Model	Section (Depth D × Width b × Thickness t) in mm and Governing load cases for column	Thickness (mm) and Governing load cases for Shear Wall
S30	300×300×20	300
	1.5DL+1.5LL	1.2 DL+1.2 LL-1.2DWLY
C30	350×350×20	400
	1.5DL+1.5LL	1.5DL-1.5EQ Y
S40	400×400×30	475
	1.5DL+1.5LL	1.5DL-1.5DWLY
C40	400×400×20	550
	1.5DL+1.5LL	1.5DL-1.5EQ Y
S50	550×550×40	700
	1.2DL+1.2LL-1.2DWLX	1.5DL-1.5DWLY
C50	550×550×35	600
	1.5DL+1.5LL	1.5DL-1.5EQ Y
S60	725×725×55	950
	1.2 DL+1.2 LL-1.2DWLY	1.5DL-1.5DWLY
C60	575×575×40	825
	1.5DL+1.5LL	1.5DL-1.5EQ Y

VI. Analysis Results

Comparison of analysis results is presented in this section.

A. Natural Time Period

In accordance with clause 5.5.1 of IS 16700:2017 [12], the natural time period of the fundamental translational modes of vibration in each of the orthogonal directions in the plan shall not be greater than 0.9 times the smaller of the natural periods of the fundamental torsional modes of vibration. In accordance with IS 1893 (Part 1):2016 [8] clause 7.1 for vertical irregular buildings, it must be ensured that the first three modes combined contribute at least 65 percent of the mass participation factor in each principal plan direction for buildings situated in seismic zones II and III. Table IV and Fig. 3 shows the time period and modal mass participation ratio of the first three modes of 30, 40, 50, and 60 stories buildings respectively.

TABLE IV

Time Period and Modal Participating Mass Ratio of 30, 40, 50, and 60 storey Individual and Conjoined Buildings

Mode	Period (sec)	Modal mass participation ratio		
		UX (X - direction)	UY (Y - direction)	RZ (Rot. @ Z)
S30 – Individual 30 storey building				
1	3.633	0.7085	0	0
2	3.56	0	0.651	0
3	3.134	0	0	0.7561
C30 – Conjoined 30 storey building				
1	2.987	0.7246	0	0
2	2.982	0	0.693	0
3	2.736	0	0	0.7183
S40 – Individual 40 storey building				
1	5.1	0.7185	0	0
2	4.822	0	0.6536	0
3	4.286	0	0	0.7489
C40 – Conjoined 40 storey building				
1	4.072	0	0.6974	0
2	4.024	0.7209	0	0
3	3.648	0	0	0.7206
S50 – Individual 50 storey building				
1	6.367	0.7161	0	0
2	6.075	0	0.655	0
3	5.008	0	0	0.751
C50 – Conjoined 50 storey building				
1	5.353	0.7305	0	0
2	5.333	0	0.7064	0
3	4.79	0	0	0.7305
S60 – Individual 60 storey building				
1	7.288	0.7212	0	0
2	6.911	0	0.6662	0
3	5.074	0	0	0.764
C60 – Conjoined 60 storey building				
1	6.679	0	0.7046	0
2	6.596	0.7222	0	0
3	5.931	0	0	0.7253

As building height increases, time period values increase and the probability of torsional mode of vibration becoming the first fundamental mode of vibration of the building decreases, as shown in Fig. 3. Conjoined buildings have shorter time periods than individual buildings, which causes the design acceleration coefficient (Sa/g) to be higher for conjoined building as compared to individual building.

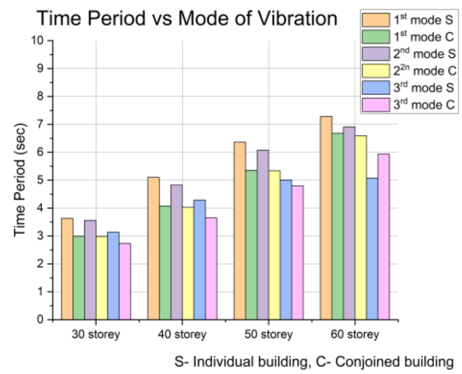

Fig. 3. Comparison of Time Period of 30, 40, 50, and 60 storey Individual and Conjoined Buildings

It is observed that, with increase in height, % increase in stiffness of conjoined building as compared to individual building reduces. So, time period of 60-storey conjoined building in torsional mode becomes higher than that of individual building.

B. Base Shear

Comparison of base shear for static and dynamic wind load as well as seismic load cases for 30, 40, 50, and 60-storey individual and conjoined buildings is shown in Fig. 4. Storey shear due to static and dynamic wind and seismic load cases in 30, 40, 50, and 60-storey individual and conjoined buildings are shown in Fig. 5.

Conjoined buildings experience significantly more base shear due to earthquake load than individual buildings. In a individual building, base shear caused by dynamic wind load is greater than earthquake load, but in a conjoined building, it is the opposite.

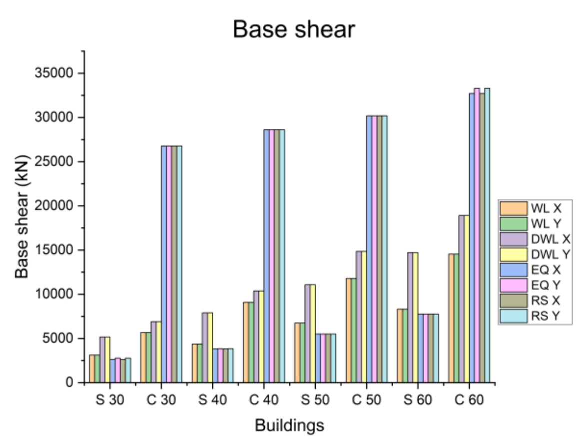

Fig. 4. Base Shear of Individual and Conjoined Buildings

C. Storey Displacement

Control of storey displacements is an important criterion for the serviceability requirements for tall buildings. Top storey displacement becomes the governing factor for the majority of tall structures. The displacement of the top storey of any building should be less than H (building height) /500 in accordance with IS 16700: 2017 [12] and table 6 of IS 800: 2007 [11]. Therefore, the maximum storey displacement that is allowed for buildings with 30, 40, 50, and 60 storey is 216 mm, 288 mm, 360 mm, and 432 mm, respectively. The story displacements of 30, 40, 50, and 60-storey tall buildings under static and dynamic wind and seismic load cases are presented in Fig. 6.

Lateral storey displacement under seismic loading for conjoined buildings are more than that of individual buildings for buildings up to 30 stories in height. But for buildings with 40, 50, and 60 stories height, conjoined buildings deflect less than the individual buildings. In an individual building, storey displacement caused by dynamic wind load is greater than that of earthquake load, but in a conjoined building, it is the opposite.

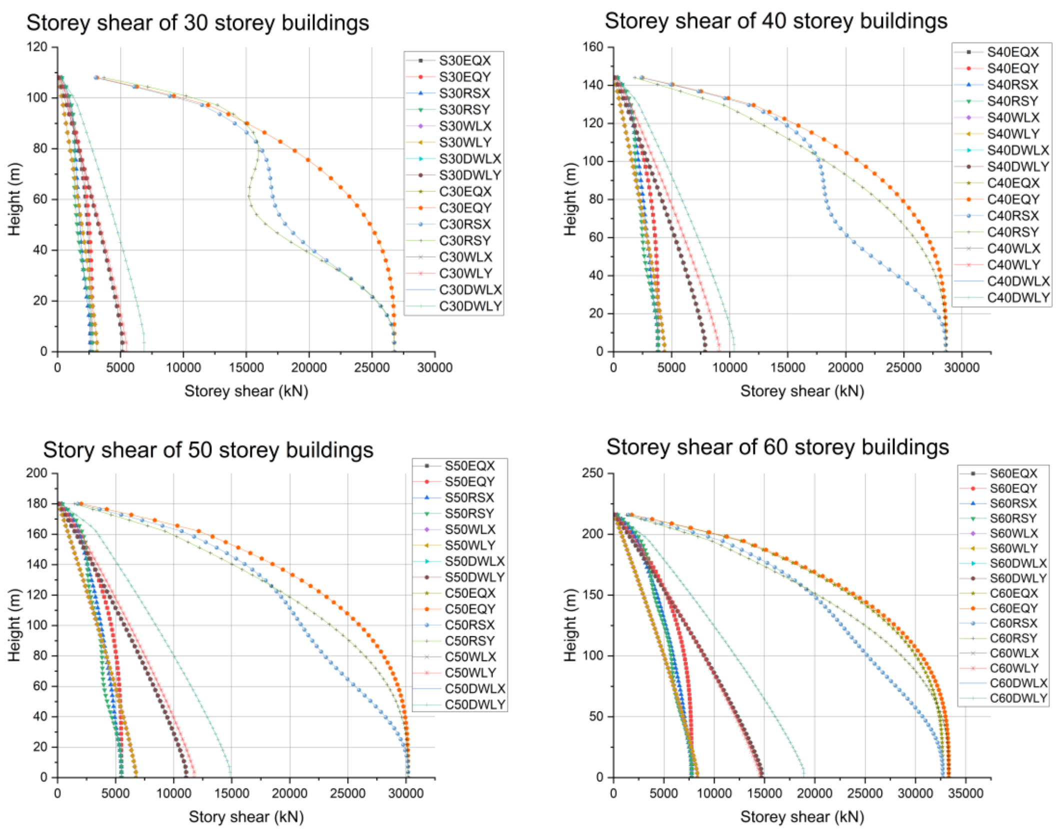

Fig. 5. Storey Shear of Individual and Conjoined Buildings

D. Inter-storey Drift Ratio

In tall buildings, the inter-story drift ratio has a big impact on human comfort criteria and performance of non-structural elements. The permitted limit for the inter-story drift ratio of a structure under service loads is 0.004 times the height of each level, as stated in clause 7.11 of IS 1893: 2016 [8] and clause 5.4.1 of IS 16700: 2017[12]. As a result, all buildings are permitted to have maximum inter-story drift ratio of 0.0144 m with a floor height of 3.6 meters. The inter-storey drift ratio of 30-, 40-, 50- and 60-storey tall buildings under static and dynamic wind as well as seismic load cases are shown in Fig. 7.

As the height of building increase, conjoined buildings experiences lower inter-storey drift as compared to individual buildings. The increased stiffness of conjoined buildings with increasing height is advantageous for controlling lateral displacements.

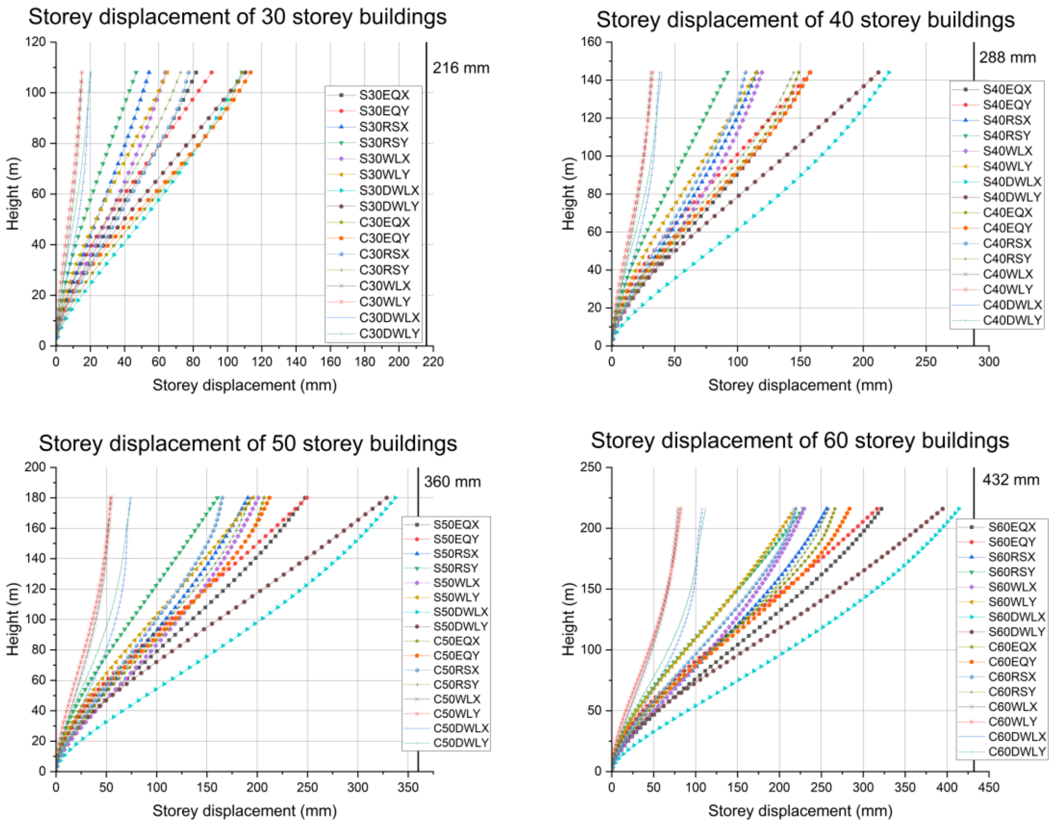

Fig. 6. Storey Displacement of Individual and Conjoined building

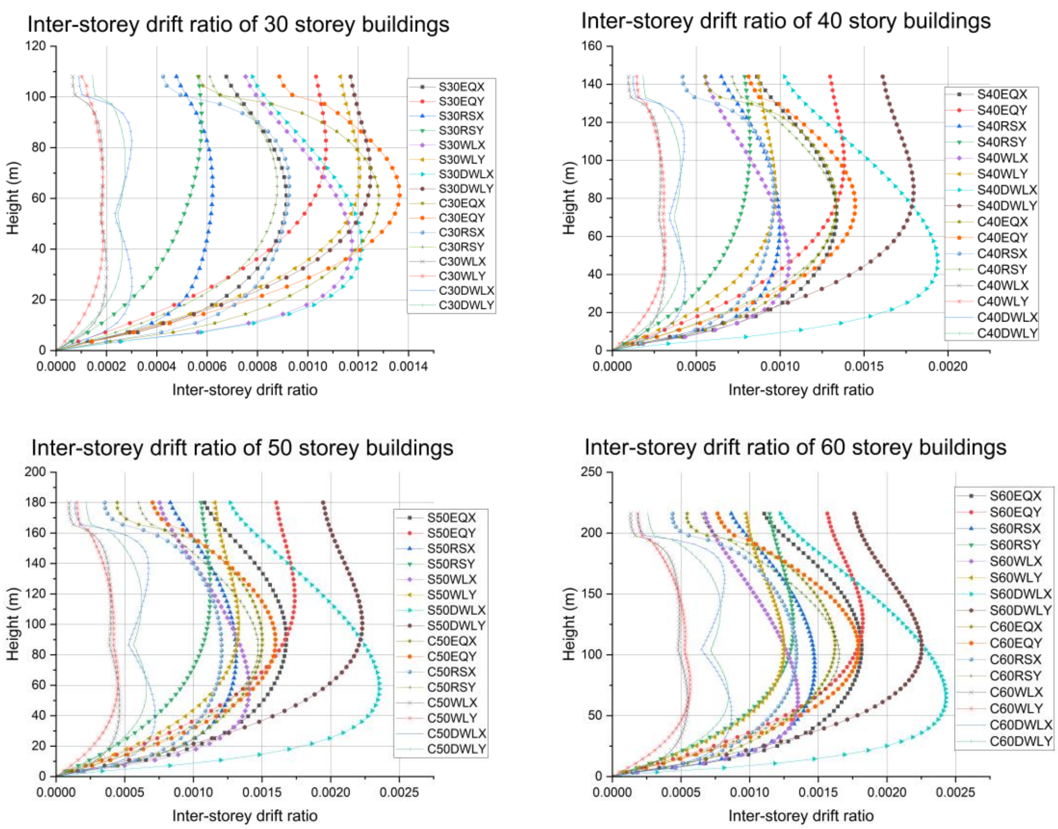

Fig. 7. Inter Storey Drift Ratio of Individual and Conjoined Buildings

VII. Conclusions

Based on a comparison of analysis and design results of 30, 40, 50, and 60-storey individual and conjoined buildings when subjected to static-, dynamic-wind and seismic loads, following conclusions are derived:

- The design forces for structural members are greater for conjoined structures than for individual structures. The difference in design forces for structural elements of a conjoined structure and individual structure reduces as the height of building increases.
- The design of conjoined buildings is governed by earthquake load, whereas design of individual buildings is governed by wind load for the buildings considered in this study. However, it is expected that with further increase in height, wind loading will govern the design of structural elements of conjoined building.
- When earthquake loads are considered, conjoined buildings experience significantly higher base shear than individual buildings. Base shear caused by dynamic wind load is greater than that caused by earthquake load in an individual building, but in a conjoined structure it is reversed. Considering that two principal buildings are experiencing a negative drag force, the dynamic wind load is lower than the earthquake load, in conjoined buildings.
- For building up to 30 storey in height, conjoined buildings deflect more than individual buildings. However, buildings of 40, 50, and 60 storey in height, conjoined buildings deflect less as compared to individual structures. Dynamic wind load causes maximum storey displacement in an individual building as compared to seismic load. While seismic load causes higher storey displacements in conjoined buildings.

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