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Lateral Behavior of Modular Steel Buildings with Diaphragm Connections

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Abstract. *Modular steel buildings are increasingly popular due to their high level of industrialization. Corner-supported modular steel buildings are typically connected by inter-module connections at the corners of each module without continuous diaphragm slab. Therefore, rigid diaphragm assumption could not be adopted when designing modular steel buildings as in-plane deformation of the slab level is significant. To address this issue, the present study introduces diaphragm connections along the edges of modules at the floor slab levels. Then the lateral behavior of modular steel buildings with and without diaphragm connections is evaluated, as well as when a rigid diaphragm is assumed in the structures. The effect of diaphragm connection on lateral behavior of modular steel building under different parameters is discussed, including modular aspect ratio, number of modules in one storey, bracing system, and number of storeys. It is concluded that using diaphragm connections could improve the lateral behavior of modular steel buildings and simplify the design process.*

Keywords: *Prefabrication; Modular steel buildings; Diaphragm connection; Lateral behavior.*

1 Introduction

Corner-supported modular steel buildings refer to the building form of prefabricated steel modular units in the factory, which are transported to the construction site, lifted and integrated. Due to its high industrialization, cost-effectiveness, environmental sustainability, and versatility, modular building has been widely used in low-rise, mid-rise, high-rise and super high-rise buildings (Duan et al., 2019; Htt et al., 2020).

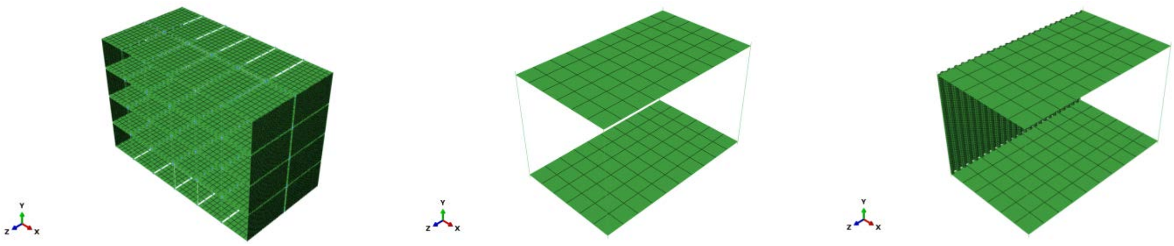
Modular steel buildings differ from ordinary steel frame buildings in that the modular buildings are assembled using inter-module connections to form the complete structure (Lacey et al., 2019) without continuous diaphragm slab. As a result of this unique feature, the lateral behavior of modular steel buildings is quite different from that of ordinary steel buildings. Numerous researchers have studied the lateral behavior of modular buildings. Lacey et al., (2020) investigated the overall behavior of modular buildings under wind and earthquake actions and found that the stiffness of inter-module connections greatly influences the overall response, with translational stiffness along the load direction having the greatest impact. Chua et al., (2019) studied the lateral stiffness of modular buildings with different simplified modes of inter-module connections and found that the axial stiffness of vertical connections significantly affected the lateral performance of modular buildings. Wang et al., (2023) proposed a distributed seismic design method that uses the inherent lateral resistance of each module for steel frame modular buildings. The study analyzed the influence of the rotating stiffness of inter-module connections on the lateral performance in elastic and elastoplastic stages via finite element analysis. Wang et al., (2022) examined the lateral displacement of semi-rigid connected column-supported modular steel structures under horizontal loads, established a corresponding lateral displacement model, proposed a highly accurate lateral displacement equation, and found that the lateral shear stiffness of vertical connections has a significant impact on lateral displacement. Liu et al., (2020) experimentally studied the lateral performance of container-type and frame-type modular buildings, and developed a theoretical model for estimating the lateral stiffness of two-story modular buildings. Ashcroft et al., (2019) proposed a more economical seismic damage-resisting system for multi-story modular buildings. Both Srisangeerthanan et al., (2022) and Bazarchi et al., (2023) proposed a new type of inter-module connection, and verified its lateral performance through experiments and numerical analysis, which provided certain guidance for the design of modular steel buildings.

To enhance the lateral performance of modular buildings, the diaphragm connection (DC) has been introduced in modular steel buildings. Modular buildings have a non-continuous diaphragm system, while diaphragm connections can improve continuity and stiffness, greatly impacting the lateral performance of modular buildings. In terms of RC structure floor deformation, Saffarini et al., (1992) conducted a study and discovered that the assumption of a rigid diaphragm does not conform to the floor deformation caused by shear walls or other factors. Pecce et al., (2017) evaluated the in-plane deformability of RC floors with traditional and innovative lightening elements in RC framed and wall structures under the influence of various factors. The results showed that the situation with walls was different from the rigid diaphragm assumption. Wei et al., (2023), the latest research shows that the diaphragm may also enter an inelastic state under earthquake action, and special attention should be paid to the performance of the diaphragm.

According to Zhong et al., (2022) , through experimental and theoretical investigation, it was discovered that the deformation of modular building floor slabs significantly differs from that when assuming a rigid diaphragm. However, the factors that affect diaphragm deformation remain unclear. Srisangeerthanan et al., (2018) also studied the influence of diaphragm flexibility on the lateral performance of modular buildings by adding diaphragm connections between the diaphragms. This study aims to comprehensively investigate the influence of diaphragm connection on the lateral performance and diaphragm deformation of modular buildings, including various factors.

2 Analysis setting and finite element model

To investigate the impact of diaphragm connection (DC) on the lateral performance of modular buildings, the ABAQUS finite element software was utilized to simulate and analyze the structural behavior. Figure 1 displays the finite element model of modular building.



(a) Whole model. (b) Single module. (c) Module with shear wall.

Figure 1. The finite element model of modular building.

To analyze the impact of various factors on the enhancement of lateral performance of modular buildings with diaphragm connections, parametric analysis of different variables of modular buildings was conducted. The variables considered in this study are aspect ratio (*L/H*) size of module (Case 1), number of modules in one storey (Case 2), lateral load resisting systems (Case 3), and number of storeys (Case 4). The main focus of this research is the lateral stiffness of modular buildings with DC. Three types of diaphragm configurations were considered, namely without DC, with DC, and rigid diaphragm.

Table 1. The design information of modular buildings in different parameter research.

Parameters	Plane module layout	Individual module size	Number of storeys	Floor and ceiling beam sections	Column section	Braces or shear walls	Floor and ceiling slab
Case 1	1 × 4	4 m × 4 m 6 m × 4 m 8 m × 4 m	1	SHS 140 × 140 × 12	SHS 100 × 100 × 9	2 mm wave steel plate	80 mm RC slab
Case 2	1 × 2 1 × 3 1 × 4 1 × 5 1 × 6	5 m × 3 m	1	SHS 140 × 140 × 12	SHS 100 × 100 × 9	SHS 100 × 100 × 9	80 mm RC slab
Case 3	1 × 4	5 m × 3 m	1	SHS 140 × 140 × 12	SHS 100 × 100 × 9	SHS 80 × 80 × 6 SHS 100 × 100 × 9 SHS 140 × 140 × 12	80 mm RC slab
Case 4	2 × 6	5 m × 3 m	2 4 8	SHS 140 × 140 × 12	SHS 100 × 100 × 9	SHS 100 × 100 × 9	80 mm RC slab

The finite element model of a modular building is constructed by assembling multiple individual modules, with each module having a height of 3 m and plan dimensions as listed in Table 1. Such module dimensions are commonly used in modular steel buildings (Lawson, (2014). The beams and columns of the modules are made of steel members, and the modules are connected by horizontal and vertical connections at the corners. Diaphragm connections are located at the floor slab level, and a 20 cm gap is reserved between the modules in both the horizontal and vertical directions to facilitate connection installation during field assembly. Braces or steel plate shear walls are added on the two sides of the building in the weak direction as the lateral resistance system. Figure 1 displays the individual modules, and Table 1 provides the design information of modular buildings for different parametric analysis.

2.1 Material

The floor beams, ceiling beams, and columns of the modular building are made of steel members, as well as the braces and shear walls. The steel material is modeled as trilinear elastoplastic, with a density of 7850 kg/m3, an elastic modulus of 200 GPa, a Poisson's ratio of

0.3, a yield strength of 355 MPa, and an ultimate strength of 470 MPa when the plastic strain is 0.02.

The floor and ceiling are reinforced concrete slabs, but for the purpose of evaluating lateral stiffness, the plasticity and damage of the floor are not considered. Therefore, the floor is modeled as an elastic floor using an elastic material. The floor has a density of 2500 kg/m3, an elastic modulus of 28 GPa, and a Poisson's ratio of 0.2.

2.2 Element

The three-dimensional finite element model of the modular building uses macro elements. Floor and ceiling beams, columns, and braces are simulated using beam elements B31. The floor, ceiling, and steel plate shear walls are simulated by shell elements S4R.

The mesh size of the beam elements is divided into a mesh for every 50 cm in length. The mesh size of the floor and ceiling is 50 cm × 50 cm, and the mesh size of the steel plate shear wall is 5 cm × 5 cm. The mesh result is shown in Figure 1 (b) and (c).

2.3 Connection

There are several types of connections within modules in modular building. The connection between the floor beam, ceiling beam, and column in each module is rigid. On the other hand, the connection between the brace and the beam and column is hinged. Furthermore, the floor slab, ceiling slab, and steel plate shear walls are all simulated using shell elements, which are connected to the beams and columns through common nodes. This method of connection helps to create a unified and continuous structure.

In traditional modular building, the connection between modules is achieved through corner connections. At the corner of each module, it is connected to adjacent modules by vertical connections (VCs) and horizontal connections (HCs). VCs ares simulated using a hinged connection, while the HC is simulated by a spring with tensile stiffness and shear stiffness equal to 20 kN/mm. For modular buildings with DCs, in addition to the HCs, there are also DCs between the floor plates of adjacent modules. A DC has a stiffness of 200 kN/mm and there is along the floor and ceiling beams at every one meter. The stiffness of both the HCs and DCs was determined using detailed finite element analysis. During the simulation outlined in this paper, only the axial stiffness and horizontal shear stiffness of the HC and DC were considered, with the other four degrees of freedom being unrestrained. Both the HCs and DCs are illustrated in Figure 2.

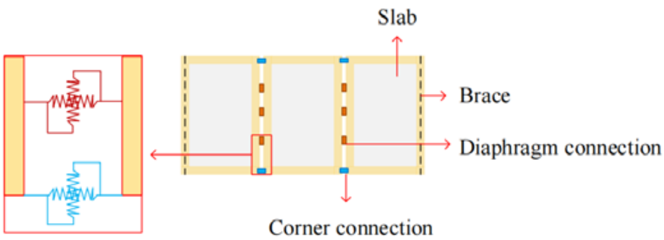


Figure 2. Inter-module connection.

2.4 Boundary conditions and loading

Based on the unique features of modular buildings, the model's boundary conditions are constrained for all degrees of freedom of the bottom column. To simulate the effect of gravity, a uniform body load is applied to each floor. Additionally, horizontal loads are applied to the ceiling beams on each floor to obtain the lateral stiffness.

3 Analysis results

The lateral stiffness of a modular building can be defined by Eq. (**1**), where, F represents the sum of the base reaction force, and x represents the mid-span displacement of the top floor of the modular building.

$$K = F/x \tag{1}$$

By comparing the lateral stiffness of modular buildings with and without DCs, as well as modular buildings with rigid diaphragm, the influence of DCs on the lateral resistance of modular buildings can be evaluated.

3.1 Effect of aspect ratio (*L/H*) size of module

When other parameters remain unchanged, varying the aspect ratio (*L/H*) of the module as 1.0, 1.5 and 2.0, the comparison of lateral stiffness is shown in Figure 3 (a).

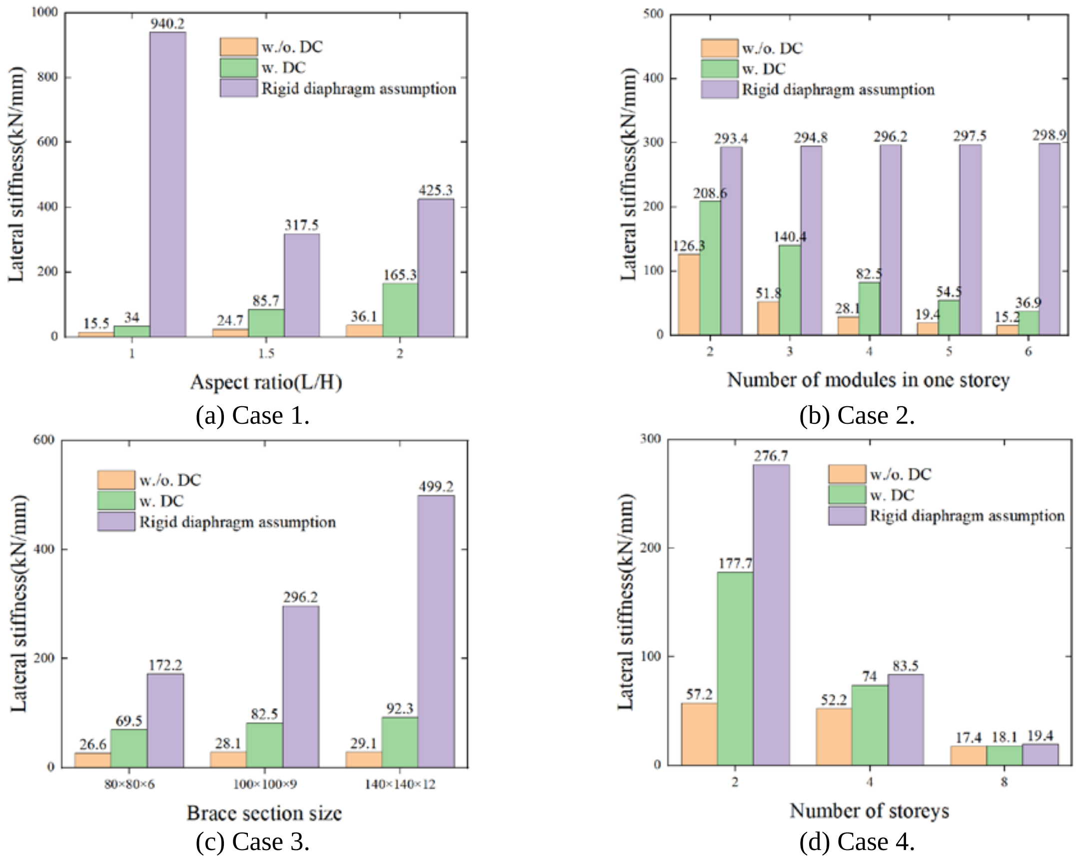


Figure 3. Comparison of lateral stiffness.

It can be observed that as the aspect ratio (*L/H*) increases, the diaphragm connection has a more effect on improving the lateral stiffness of modular buildings. This can be attributed to the fact that as the module length increases, the number of DCs between modules also increases, which reduces the relative lateral displacement between modules. The lateral stiffness of modular buildings with DCs becomes closer to those with rigid diaphragm. However, the lateral stiffness of modular buildings with DCs is far smaller than that with rigid diaphragm.

3.2 Effect of number of modules in one storey

When other parameters remain unchanged, varying the number of modules in one storey of the module as 1 × 2, 1 × 3, 1 × 4, 1 × 5 and 1 × 6, the comparison is shown in Figure 3 (b).

The analysis shows that as the number of modules in one storey increases, the influence of DCs on the lateral stiffness of modular buildings first becomes more significant and then decreases to a certain extent. When the number of modules is relatively small, the increase in lateral stiffness is more significant because the number of gaps between modules increases, and the proportion of inter-module connection dislocation in lateral deformation increases. However, when the number of modules reaches a certain level and continues to increase, the effect of DC becomes less significant, mainly because the intermediate module is too far away from the lateral resistance system, and the transmission of lateral forces becomes less effective. Furthermore, when the number of modules is relatively small, the lateral stiffness of modular buildings with DCs is closer to that of rigid diaphragm.

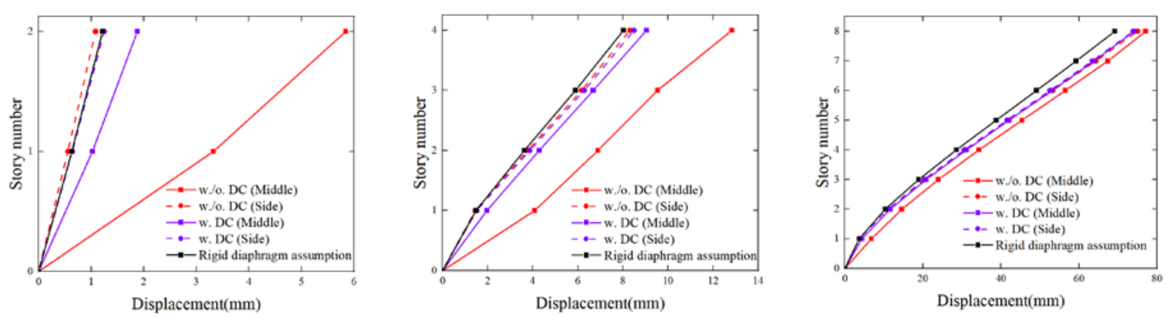
3.3 Effect of lateral load resisting systems

When other parameters remain unchanged, varying the brace section of the module as SHS 80 × 80 × 6, SHS 100 × 100 × 9, SHS 140 × 140 × 12, the comparison is shown in Figure 3 (c).

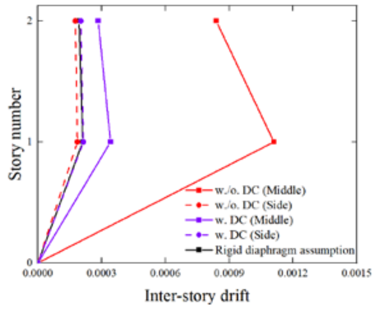
The analysis suggests that the effect of DCs on the lateral stiffness of modular buildings becomes more significant as the lateral stiffness of the lateral resistance system increases. However, with the increase of the lateral stiffness of the lateral resistance system, the difference between the lateral stiffness of the modular building with DC and the modular building with the rigid diaphragm becomes larger.

3.4 Effect of number of storeys

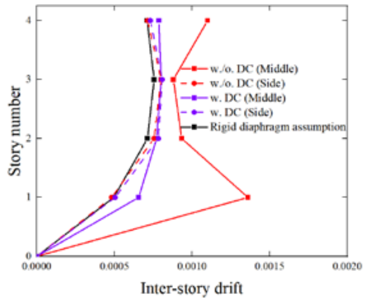
When other parameters remain unchanged, varying the number of storeys of the module as 2, 4 and 8, the comparison is shown in Figure 3 (d). The lateral displacement of each storey and the inter-story drift of the 2-, 4- and 8-storey modular building are shown in Figure 4.



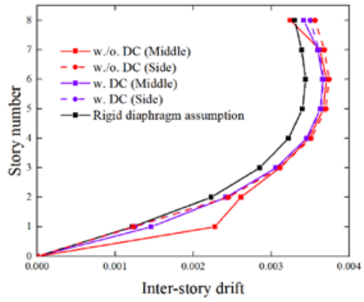
(a) Storey displacement (2-storey). (b) Storey displacement (4-storey). (c) Storey displacement (8-storey).



(d) Inter-story drift (2-storey).



(e) Inter-story drift (4-storey).



(f) Inter-story drift (8-storey).

Figure 4. Displacement of each storey and inter-story drift of 2-, 4- and 8-storey modular building.

As the number of storeys in modular buildings increases, the enhancement of lateral stiffness due to DCs becomes less significant. Additionally, the higher the multi-storey buildings, the lateral stiffness of modular building with DCs is closer to the with rigid diaphragm. This is because the displacement between floors is primarily influenced by the stiffness of VCs, whereas diaphragm connections have a greater effect on the in-plane performance of each floor. To improve the lateral stiffness of multi-storey modular buildings, it may be helpful to implement additional structural measures between the two vertical modules. However, inter-story drift in modular buildings with diaphragm connections still differs greatly from that of the assumption of a rigid diaphragm. Using this assumption, the ground floor and second floor in a 2-storey modular building with DCs will be underestimated by 38.3% and 31.7%. The ground floor and fourth floor in a 4-storey modular building with DCs are underestimated by 24.4% and 9.5%. The inter-story drift of the ground floor, fifth floor, and sixth floor in an 8-storey modular building with DCs will also be underestimated by 16.4%, 6.3%, and 6.0%, respectively.

4 Conclusion

Through finite element parameter analysis, the influence of diaphragm connection on lateral performance of modular buildings is revealed, and the conclusions are as follows:

- As the aspect ratio (*L/H*) of modular buildings increases, the impact of DCs on lateral stiffness becomes more significant. Additionally, the lateral stiffness of modular buildings with DCs increasingly approaches that of rigid diaphragm. However, despite improvements in the lateral stiffness of modular buildings with DCs, there are still differences when compared to those with the assumption of a rigid diaphragm.
- As the number of modules in one storey increases, the effect of DCs on the lateral stiffness of modular buildings initially becomes more significant but then decreases to a certain extent. When the number of modules is relatively small, the situation is closer to that of rigid diaphragm. However, as the number of modules increases, the difference between modular buildings with DCs and the assumption of rigid diaphragm becomes more pronounced.
- The influence of DCs on lateral stiffness becomes more significant as the lateral stiffness of the lateral resistance system increases. However, as the lateral stiffness of the lateral resistance system increases, the difference in lateral stiffness between modular buildings with DCs and those assumed to have a rigid diaphragm also becomes larger.

- As the number of stories increases, the impact of DCs on lateral stiffness becomes less significant. Furthermore, higher numbers of stories lead to modular buildings with DCs approaching the assumption of a rigid diaphragm. In modular buildings with high numbers of stories, DCs have little influence on lateral stiffness. However, the inter-storey drift in modular buildings with or without DCs is larger than that with rigid diaphragm.

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