Industrial Building System (IBS): A Unique Intra-Module Connection on Modular Steel Building (MSB)

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Abstract. Modular Steel Building (MSB) provide benefits towards green building technology such as minimum wastage, faster build time and cost-efficiency. The intra-module connection is the most important aspect of MSB construction since it has a significant impact on overall structural stability and robustness. A novel intra-module connection was proposed for the MSB. The proposal was designed to suit the illustrative five-storey hexagon shape modular steel building that possibly imagines by Architect. Two analyses phases are being presented, namely the Macro and Microanalysis model. The former is the stage for global analysis design of the proposed five-storey hexagon shape modular steel building via SAP2000. The latter is the local intra-module connection behaviour analysis using ABAQUS software. Linear and nonlinear static analyses were carried out on the proposed intra-module connection under the vertical applied load. In this work, the failure of the connection under the given load was governed by the hexagon diaphragm, while the fin plate demonstrates the least affected constitutive component. It anticipates that the suggested unique intra-module connection will encourage architects to employ modular steel construction designs with greater flexibility. Future research will concentrate on the parametric study to improve the performance of the diaphragm and the connection's limitations.

1. Introduction
One of the strategic thrusts to achieve the Sustainable Development Goals (SDG) is by pursuing green growth for sustainability and resilience. Sustainability is quantified in terms of various measures of environmental, social, and economic performance [1]. The sustainable benefit of modular steel construction in environmental, economic, and social has been widely discussed by Lawson et al. [2].

The construction of modular steel structures is actively being used over a decade ago. Yet, very limited studies, either experimentally or numerically, have discussed theoretical aspects, particularly inter and intra module connection. The standard intra-module connection used bolted connection to connect parallel flange channel known as PFC to mild steel square hollow section (SHS). Researcher developed double angle cleats connection to connect universal beam (UB) and rectangular hollow sections (RHS) [3]. While another researcher, in 2019, developed an innovative connection for intra-module and inter-module connection called Vector Bloc Modular Connector [4]. The rectangular hollow steel (RHS) section is welded to the connector and bolted to the column-to-beam connection.

According to research performed by [5][6][7], the current key limits of inter and intra-module connection applications include the lack of an established guideline to assist structural designers in building economic and safe connection designs to exploit modular structural fully. A review carried out by [5] summaries many experimental works [6]-[13] being conducted that contributed to various new innovative inter-module connection designs to suits any architectural demand. For instance, studies
conducted by Annan et al. [10], [11] give insightful knowledge for practices, revealing that consideration of the true behaviour of direct welding leads to a distribution of forces and moments that is different from those found in traditional steel buildings. As a result, the regression function was utilised to generate a simplified analytical model to capture such behaviour in actual practice, leading and assisting the structural engineer in making an accurate forecast on the design of modular steel flooring. Apart from [5], several other scholars have attempted to improve the inter-module connections. Park et al. [5] presented a bolted connection for modular steel construction with the adjacent module unit is bolted directly to the cruciform gusset plate. Chen et al. [6] proposed and tested a beam-to-beam bolted connection. Deng et al. [9] proposed a new connection with socket-shaped tendons and cruciform gusset plate to connect the module unit. Despite all the rigorous design [4]–[13], the proposed connections perhaps well suited for the structural component of the modules but may not work well with the internal finishes and the use of the floor and walls, which highlight the manufacturing efficiency.

Moreover, connections [4-13] connect the upper module and lower module by bolting the ceiling beam and floor beam without connecting the columns, which is presumed to lead to indirect uplift load transfer when subjected to lateral forces, such as wind and earthquake. Additionally, limited experience and technical knowledge among architects & engineers, plus no component standardisation causing the upfront cost increase for component mould. The issues have caused insecurity on the modular product quality and certification in terms of safety, affecting the economic growth of the modular construction. Research conducted by [14] highlighted that the current modular system is less adaptable, with a conventional rectangular shape that appears to constrain modern architectural design innovation. Research in [15] reported that the modular steel building is more suited for a lower-income family. These problems must be solved at the fundamental level, whereby there is an urgent need to formulate a robust universal design concept of intra-and inter-module connection that suits the multi-purpose designs of the building. However, all of the connections listed are only relevant for 90° column-to-beam connections, hence the connections are only suitable for the modular's rectangular design. Some researchers stated that the conventional modular steel building existing in the industry is too plain and inflexible [16]. Usually, the architects tend to propose a complex yet aesthetically presentable building. This work proposed a novel intra-module connection for a modular steel construction building. The proposed novel intra-module connection was designed to suit the illustrative five-storey hexagon shape modular steel building that possibly imagine by Architect. The failure mechanism of intra-module connection under shear and the lateral load was analysed using linear and nonlinear static analyses via the ABAQUS Finite Element Analysis (FEA) software.

2. Proposed Modular Steel Building

The proposed modular steel building is shown in figure 1. All dimensions presented in figure 1 are in unit mm. The height of the proposed modular steel building is 3 meters with a side width of 2.5m each. The three-dimensional view and the plan views of the proposed modular steel building are illustrated in Sketch up and shown in figure 2. The proposed modular steel building is then modelled and designed in SAP2000. The dead load was directly taken from the default self-weight of the section material used in the SAP2000, while the other actions were the ceiling (1kN/m²), floor (3.3kN/m²), wall (3.8kN/m), and wind(0.65kN/m²). The modular structure was designed to the ultimate limit state (ULS), in which the values of the partial and combination factors were taken as given in the UK National Annex. These values are subject to modification in the National Annex, which must be consulted. In this context, structural connections' components are steel channel section, fin plate, bolt, nut, and diaphragm. Table 1 provides the detailed design section that has been proposed. Later, all the listed structural section in table 3 was used for modelling in ABAQUS FEA.
Figure 1. Proposed modular steel building.

Figure 2. Illustration of Modular Steel Building

Table 1. Design sizes of component of the intra-module connection.

| Component of the connection                  | Sizes of the component                        |
|---------------------------------------------|------------------------------------------------|
| Main Frame                                  | Primary steel frame = C10 x 30                 |
|                                             | Secondary steel frame = C6 x 8.2               |
| Circular Hollow Structural Section          | Circular HSS 6.88 x 0.25mm                     |
| Diaphragm                                   | Hexagon shape with a thickness of 20mm        |
| Bolt and Nuts                               | Size 16mm with grade 8.8                      |
| Fin Plate                                   | 200 x 200 x 20mm                              |

3. Verification of the finite element modelling method

The single-lap joint shown in figure 3 was used to examine the accuracy of the finite element modelling technique to model the connection. The top and bottom plates are grade S355 with 200mm x 200mm with a thickness of 25mm. The bolt size (d) is 16mm for the single lap joint, and the bolt hole size (d₀) is 18mm. It has a high tensile bolt strength grade of 8.8. A 10N/mm² pressure load, P, was applied parallel into the longitudinal direction x-axis. Next, the load capacity of the connection was calculated.
by using the formula as in equation (1). The resistance capacity for this connection is determined to be 60.288kN as in equation (2).

$$F_{v,Rd} = a_v f_{ub} \frac{A_s}{\gamma_{m2}}$$

(1)

$$F_{v,Rd} = 0.6 \times (800) \times \frac{157}{1.25} = 60\,288\,N = 60.288\,kN$$

(2)

The single-lap joint was then modelled in ABAQUS version 6.14. A continuum element that was used to model the two plates is naming as C3D6 whereby first letter is represent continuum stress/displacement, second letter is its assymetric deformation (optional), third is the no of nodes, forth is reduce integration and lastly is small-strain formulation in ABAQUS/ Explicit. Meanwhile, the CCL24 element was used to model the bolt and nuts. The characteristic of the material assigned in the ABAQUS was presented in table 1. The deformable solid element with extrusion is used to model the steel channel section, circular hollow structural section, diaphragm, bolts, nuts, and fin plate in ABAQUS. For bolts, it was initially created with two different components: the head and the thread. The head and thread were then kept in intersecting boundaries to form a component. All the connection components created were assembled in the assembly section, as presented in figure 4. Linear static analysis was carried out to compare the shear resistance capacity design between the manual calculation and ABAQUS analysis. From the ABAQUS analysis conducted, the shear force reactions were then measured at the interface between the two plates and compared with the hand calculation designed according to calculation specified in [17]. The designed shear resistance per bolt comparison between ABAQUS and applied shear is shown in table 2 and indicates an excellent agreement with a difference of only 0.28 percent. The shear load obtained in ABAQUS is lesser than the ultimate design shear calculated using the calculation specified in [18], indicating that the single lap joint connection is able to resist the 10N/mm² (50kN) applied load. The deformed shape obtained from ABAQUS FEA software is shown in figure 5. The plates and bolt are allowed to move in X-direction. Thus, the moving of the plates will pull out the bolt from its original condition. Hence, the pulling out results show that the bolt experience high stress compared to other components. Figure 4 shows the undeformed shape before pulling out opposite the X-direction. Meanwhile, figure 5 shows the deformed shape of the single lap joint connection model after being pulled out by 10N/mm² pressure load (equal to 50kN force), respectively. Figure 6 shows the resultant force of the bolt that was pulled out.
4. Finite Element Modelling and Analysis of the proposed Intra-module connection.

The proposed intra-module connection shown in figure 7 was modelled and analysed in ABAQUS to investigate the governing failure mechanism. The intra-module connection consists of a steel channel, circular hollow, diaphragm, bolt, nut, and fin plate. The dimensions and materials for the steel C-channel, circular hollow, and fin plate are stated in table 1 and table 3. A continuum element C3D6 was used to model the circular hollow section, fin plate and diaphragm. Meanwhile, the CCL2 element was used to model the bolt and nut. The bolt and nut are fixed by using tie constraint. Nonlinear analyses via the ABAQUS FEA software is used to analyse the innovated novel intra-module connection. A general nonlinear Static, Riks method is used to simulate the intra-module connection's behaviour up to failure. The initial axial load is exerted 1000N downward at the end of the beam (refer figure 7), and it is incremented by time until failure.

Elastic-plastic materials are assigned in accordance with table 3. All steel elements for the diaphragm, circular column and c-channel are assigned as steel grade S275. The fin plate is assigned as steel grade S355, bolts and nuts are designated as high tensile steel Grade 8.8, respectively. For elastic characteristics, Young's Modulus is 210000 N/mm² and its Poisson's Ratio is 0.3. The density of steel
is 7850 kg/m$^3$. The circular column is tied with a diaphragm using tie constraint. The fin plate is joined together by ties constraints perpendicular to the circular hollow column between the diaphragms. The c-channel is connected via tie constraint at the top and bottom flanged to the diaphragm. Contact interactions are used to connect the bolts and fin plate to the c-channel. All the contact interaction modelling used the technique master and slave whereby the slave element (loose part) will be tied to master elements that are rigid to form a body of the structure. The type of “encanstre” boundary condition is assigned at two places; at the bottom of the column and the side of the diaphragm (with an assumption that other c-channel members hold the other perimeter of the diaphragm). The modelling results such as stresses, strains, displacements, force/reaction and contact are requested and recorded in field and history output.

5. Result and Discussion

5.1 Failure mechanism of intra-module connection

The incremental vertical load was applied to the proposed novel intra-module connection until it failed. Every component of the connection was observed via step frame analysis to identify the critical failure mechanisms. The critical failure mechanism is the first component of the connection that has passed their Von Mises Stress. The first component that passed its original yield stress is the most severe, while the last component that passed its actual yield stress is the least severe. At the same time, the type of failure mechanism or failure mode acted on components of the connection have been identified and shown in table 4. The ABAQUS simulation analysis reveals that the diaphragm has achieved its yield capacity when it's reached 23440N (23.44kN) axial load, which is estimated about 23 times its initial applied load. In the proposed novel intra-module connection, the diaphragm is experiencing the most severe failure compared to other connected components. In comparison, the bolt and nut are the least severe among the members of the connection. The diaphragm was the first to experience local buckling at the top of the column facing the XY-axis for the finite element model under consideration. The increase of load and deformation of the diaphragm has indirectly pulled the circular hollow column and caused it to fail under flexural failure. The applied force on the c-channel has pushed the column and the diaphragm down, causing the torsional-flexural failure seen in figure 8.

Table 3. Stress and strain value for S355 Steel Plate and Bolt and Nut.

|       | S355 Steel | Bolt and Nut | S275 Steel |
|-------|------------|--------------|------------|
| Stress (kN/m$^2$) | Strain (mm/mm) | Stress (kN/m$^2$) | Strain (mm/mm) | Stress (kN/m$^2$) | Strain (mm/mm) |
| 0     | 0          | 0            | 0          | 0              | 0               |
| 355   | 0.002      | 640          | 0.003      | 275.0          | 0.001           |
| 355   | 0.015      | 750          | 0.008      | 275.0          | 0.015           |
| 397   | 0.026      | 800          | 0.028      | 315.4          | 0.037           |
| 475   | 0.057      | 640          | 0.118      | 347.7          | 0.058           |
| 510   | 0.110      | 66           | 0.139      | 373.0          | 0.080           |
| 504   | 0.140      |              |            | 392.4          | 0.101           |
| 489   | 0.170      |              |            | 406.9          | 0.123           |
|       |            |              |            | 417.3          | 0.144           |
|       |            |              |            | 424.1          | 0.166           |
|       |            |              |            | 428.2          | 0.187           |
|       |            |              |            | 429.9          | 0.209           |
|       |            |              |            | 429.7          | 0.230           |
Meanwhile, the axial load acted on the structure cause the c-channel to experience local buckling at the top and bottom flanges. Flexural failure was observed occurred on both of the circular hollow sections and along with the diaphragm. The plate with the highest grade only accounted for the stress of 357.50 N/mm², which is the lowest of the connecting members. The mises stress that act on the bolt and nut section is the highest among others. The plastic deformation that occurs at the c-channel, column, diaphragm and plate connection are shown as in figure 9 and figure 10, respectively. The highest strain that happened was in the diaphragm, which probably indicated that the diaphragm governed the failure mechanism.

![Images of deformation](image_url)

**Figure 8.** The failure mechanism of the connection.

![Images of deformation](image_url)

**Figure 9.** View of the c-channel section under plastic strain deformation.

**Figure 10.** Isometric view of column, diaphragm and plate connection under plastic strain deformation.

**Table 4.** Summary of original yield stress, mises stress, plastic strain and failure mode of every part of the proposed novel intra-module connection.

| Structure Component       | Original Yield Stress (N/mm²) | Mises Stress (N/mm²) | Plastic Strain | Failure mode                      |
|---------------------------|-------------------------------|---------------------|----------------|-----------------------------------|
| C-Channel Section         | 275                           | 429.70              | 0.73           | Local buckling of the top and bottom flanges |
| Circular Hollow Column    | 275                           | 429.80              | 1.57           | Flexural-torsional buckling       |
5.2 *The load-displacement behaviour*

Figure 11 depicts the force vs displacement relationship measured at the point where the load is applied on the PFC. As can be seen, the ultimate load imposed on the PFC prior to the structural system becomes unstable is 249.63kN, with a vertical displacement of 435.71mm. The diaphragm was the first to yield at a load capacity of 23.4kN, followed by the top and bottom flanges of the PFC (refer to figure 8b). As the PFC deformed at large displacement, it caused the diaphragm and column to be pulled downward and strained to 1.57 to 2.02, respectively. In addition, the diaphragm and the column were observed to experience slight torsional-flexural deformation under the imposed load. One of the possibilities was due to the geometrical shape of the diaphragm. The intra-module structure member was joint at one of the adjacent diaphragm parameters and was rigidly restrained on the other adjacent diaphragm parameter, as shown in figure 7. As previously said, the diaphragm was welded to one side of the column's circumference; therefore, as the PFC moving downward, the adjacent side of the diaphragm parameter has also been pulled and twisted downward together with the column. The exclusion of the secondary beams in restraining the main PFC laterally was also the additional reason for such deformation behaviour. The behaviour of the moment-chord rotation characteristic was also observed under the incremental applied load. It can be seen that the highest moment measured at the PFC-diaphragm-column connections was about 280kNm, with chord rotation is at 0.35 mm/mm. The moment capacity obtained has exceeded the plastic yield moment capacity of the PFC, column and diaphragm. Such observation can be seen in figure 9 and figure 10, in which the equivalent plastic strain has occurred at the top and bottom of the PFC flanges, the diaphragm and one spot at the fin plate.

![Figure 11. Force vs displacement curves of the intra-module structures.](image-url)
6. Conclusion
A new design scheme of the intra-module connection for the innovative hexagon modular steel building has been proposed. The novel intra-module connection has been successfully evaluated. The failure mechanism of the novel intra-module connection under the applied incremental vertical load using the ABAQUS FEA software has been determined. For the model under consideration, the failure of the proposed connection is probably governed by the diaphragm and depends on how the load is applied to the connection. The analysis shows that the proposed hexagon diaphragm, which was welded to the circular hollow column, tends to experience flexural torsional buckling. One of the main reasons is the hexagon shape diaphragm used to connect the intra-module structural members and the secondary beam's exclusion to restrain the main PFC laterally. In this work, the failure of the connection under the given load was governed by the hexagon diaphragm, while the fin plate demonstrates the least affected constitutive component. It anticipates that the suggested unique intra-module connection will encourage architects to employ modular steel construction designs with greater flexibility. Future research will concentrate on the in-depth parametric study to improve the performance of the diaphragm and the connection's limitations.

7. Recommendation
The ABAQUS FEA software modelling in this work does not restrain the steel channel section with any beams or slabs. As a result, the steel channel section should be restrained with a secondary beam of steel channel section spaced at 0.6 m intervals to prevent flexural-torsional buckling. It is also significant to physically test the unique intra-module connection that has been proposed. The performance of the suggested innovative intra-module connection under dynamic stresses such as fatigue and earthquake would be a fascinating future field to research.

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