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"Study of Interlocking Inter-Module Connection for Modular Steel Buildings"

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Abstract— *'Modular construction' is a term used to describe the use of factory-produced pre-engineered building units that are delivered to site and assembled as large volumetric components or as substantial elements of a building. The modular units may form complete rooms, parts of rooms, or separate highly serviced units such as toilets or lifts. The collection of discrete modular units usually forms a self-supporting structure in its own right or, for tall buildings, may rely on an independent structural framework.*
Interconnection of frame members and modules is critical to the capability of modular buildings to withstand applied loads. Despite the need for a thorough understanding, studies on the connections are limited. Connections are grouped into three types: inter-module, intra-module, and module to foundation. In the present study, a novel inter-module connection with interlocking arrangement is tested with numerical simulations (ANSYS simulation) for axial tension, shear and moment. The results of the numerical simulations are verified with analytical calculations. The numerical study is done using FEM software, ANSYS 2020 R2, for three models with changes in sectional properties and bolt arrangements while keeping the material properties constant. Model 1 is the base model from literature (Lacey et al, 2020), and model 2 and model 3 are the structurally enhanced models for the said loading conditions. The three models are compared based on equivalent stress (von Mises stress) and total deformation. Of the three models, it was found out that the model 3 is structurally stronger as compared to other two models when all three are subjected to the same said loading. Also the model 2 was observed to be structurally better than the initial model 1.
Keywords: *Inter-module connection, modules, inter-module, intra-module, simulation, inter-locking, MathCad, ANSYS*

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I. INTRODUCTION

Steel structure is a metal structure, which is made of *structural steel* components connect with each other to carry loads and provide full rigidity. *Structural steel* is steel construction material, which fabricated with a specific shape and chemical composition to suit a project's applicable specifications. Because of the high strength grade of steel, this structure is reliable and requires less raw materials than other types of structure like concrete structure and timber structure.

In modern construction, *steel structures* is used for almost every type of structure including heavy industrial building, high-rise building, equipment support system, infrastructure, bridge, tower, airport terminal, heavy industrial plant, pipe rack, etc.

'Modular construction' is a term used to describe the use of factory-produced pre-engineered building units that are delivered to site and assembled as large volumetric components or as substantial elements of a building. The modular units may form complete rooms, parts of rooms, or separate highly serviced units such as toilets or lifts. The collection of discrete modular units usually forms a self-supporting structure in its own right or, for tall buildings, may rely on an independent structural framework.

Modular Buildings:

A modular building is a pre-engineered steel structure, which means its components, or modules, are built in a factory setting according to the same codes as any traditionally constructed buildings. The finished modules are transported by commercial trucks to a construction site, where a builder assembles them. Each module is installed to form a self-supporting structure that can support another modular unit on top. While this can be an advantage for compartmentalized vertical construction, modular buildings have limits when it comes to large-scale facilities. This becomes especially true for buildings that span wider than a semi-truck bed.

Attributes of Modular Construction:

The use of modular and other lightweight forms of building construction is increasing. The benefits of modular construction, relative to more traditional methods, include:

i. Economy of scale through repetitive manufacture
ii. Rapid installation on site (6-8 units per day)
iii. High level of quality control in factory production
iv. Low self-weight leading to foundation savings
v. Suitable for projects with site constraints and where methods of working require more off-site manufacture
vi. Limited disruption in the vicinity of the construction site
vii. Useful in building renovation projects, such as roof top extensions
viii. Excellent acoustic insulation due to double layer construction
ix. Adaptable for future extensions, and ability to be dismantled easily and moved if required
x. Robustness can be achieved by attaching the units together at their corners
xi. Stability of tall buildings can be provided by a braced steel core.

II. METHODOLOGY

The methodology for Study of interlocking inter-module connection for modular steel buildings**"** project can be divided into several stages as follows:

- **Planning and Preparation of drawings:** This stage involves preparation of drawings of the IL-IMC model.
- **Perform Simulation Tests on the specimen (for validation):** In this stage, shear, axial tension & moment tests are perfomed.
- **Analytical verification of tests (for validation):** In this stage, calculations for validation are performed.
- **Simulation on FEM Software:** In this stage, the software tool is thoroughly tested to ensure that it is functioning correctly and providing accurate results. This includes testing for various input scenarios & verify the test results.
- **Alternative Solutions:** Preparation of the alternative model by varying bolt locations if needed.
- **Results & Conclusions**

Planning:

The design plays a vital role in the analytical as well as numerical study. The model from the literature was taken directly considering the dimensional properties and the material properties. And three types of loading cases were planned to be applied to the connection model viz axial loading (tension), shear loading and moment loading. For numerical analysis modelling will be done using CATIA software, which will be analyzed using FEM analysis in ANSYS 2020 R2. For analytical validation MathCAD 15 software will be used and for empirical analysis six specimens should be fabricated and tested for three types of loadings (two specimens for each loading case).

3D Modelling of IMC:

3D modelling of the inter-module connections was done using CATIA which was further imported into ANSYS for FEM analysis. The geometric details of the connections are shown in figures below.

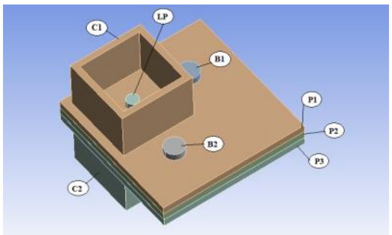


Figure 1: Model 1 (3D view)

C1: 75 x 75 x 6, 50 long
C2: 75 x 75 x 6, 50 long
P1: 150 x 150 x 8 plate
P2: 150 x 150 x 8 plate
P3: 150 x 150 x 8 plate
B1: M12, 4.6 grade
B2: M12, 4.6 grade
LP: R12 x 50, locating pin

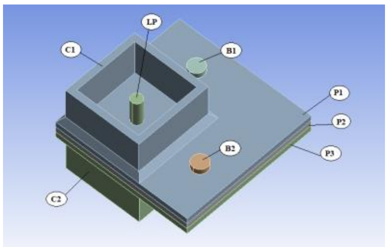


Figure 2: Model 2 (3D view)

C1: 100 x 100 x 8, 50 long
C2: 100 x 100 x 8, 50 long
P1: 179 x 179 x 8 plate
P2: 179 x 179 x 8 plate
P3: 179 x 179 x 8 plate
B1: M12, 4.6 grade
B2: M12, 4.6 grade
LP: R14 x 50, locating pin

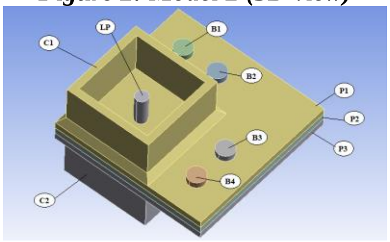


Figure 3: Model 3 (3D view)

C1: 100 x 100 x 8, 50 long
C2: 100 x 100 x 8, 50 long
P1: 179 x 179 x 8 plate
P2: 179 x 179 x 8 plate
P3: 179 x 179 x 8 plate
B1: M12, 4.6 grade
B2: M12, 4.6 grade
B3: M12, 4.6 grade
B4: M12, 4.6 grade
LP: R14 x 50, locating pin

Material specifications:

Material used in this study is structural steel and specifications of which are as follows:

1. Structural steel having yield strength of 250 MPa, ultimate strength of 410 MPa, tangent modulus of 1450 MPa, poisons ratio of 0.3, young's modulus of 200GPa and coefficient of friction steel plate interactions is taken as 0.3, is used.
2. Stress-strain curve is defined using bilinear model.
3. MIG welding is used for column - plate connection and plate - locating pin connection.
4. Bolts used for connection are of 4.6 grade.

Loading and boundary conditions:

Three types of loadings are applied on the models individually in this study that are shear force, axial-tension force and moment and the models are analyzed for the same loadings.

The direction of loadings and the boundary conditions are shown in the figure 4.

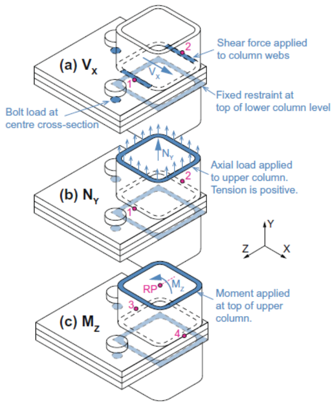


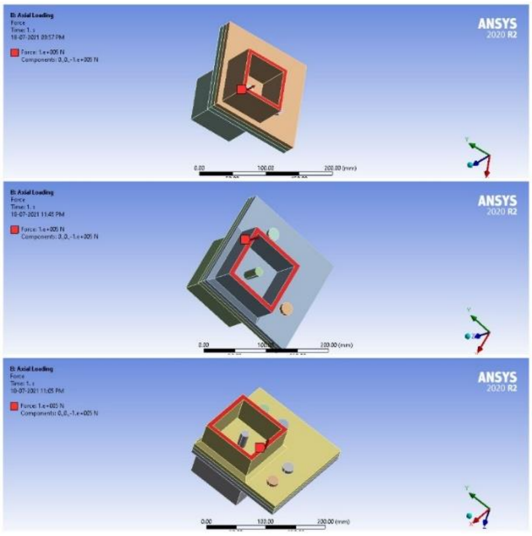
Figure 4: Loading and Boundary conditions

III. NUMERICAL SIMULATIONS

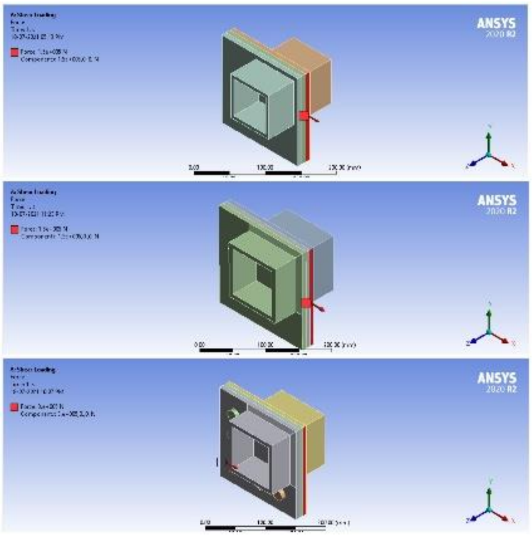
Opening Statement:

The numerical simulation which was carried out on the three models. In this study, the base model (model 1) is taken from literature[13] which is further enhanced for sectional dimensions and bolt arrangements (model 2 and model 3) and is analyzed using FEA.

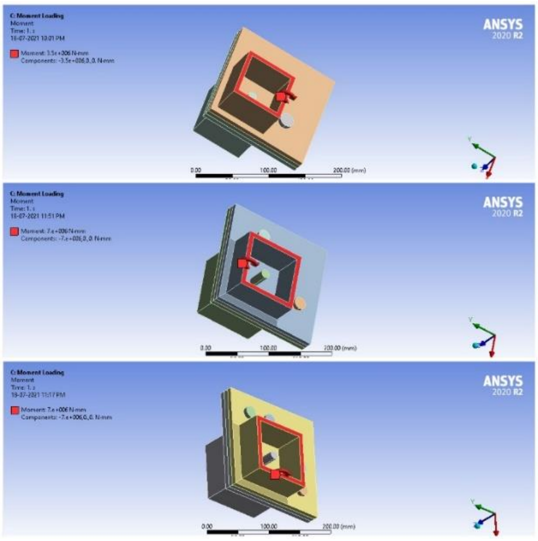
The geometric models are prepared using CATIA and the models are then imported into ANSYS for finite element analysis. Material properties are taken as specified earlier. For contact properties bolt to plate interactions are taken as bonded, locating - pin to plate interaction are taken as bonded and plate to plate interaction are taken as frictional with the coefficient of static friction value of 0.3. Meshing element used is of tetrahedron type with the mesh size of 2.5 millimeters. Loading and boundary conditions are taken as specified in figure 4. And loads are applied according to the type of tests in gradual manner using sub-steps. The numerical analysis results consist of equivalent stress (von Mises stress) and total deformation.



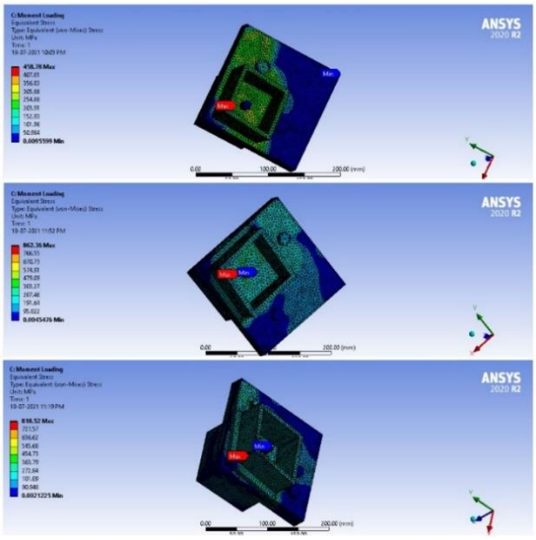
Axial: Total Deformation in ANSYS



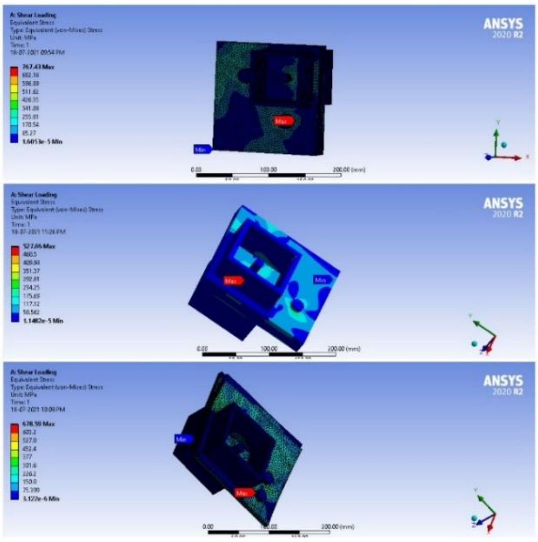
Axial : Support in ANSYS



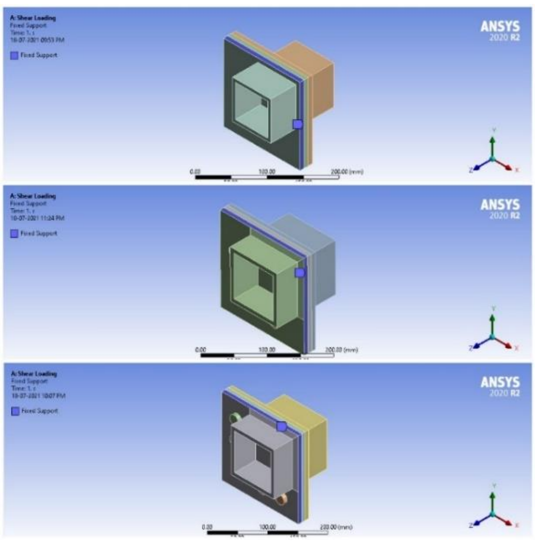
Moment: : Support in ANSYS



Moment: Equivalent stress (von-Mises) in ANSYS



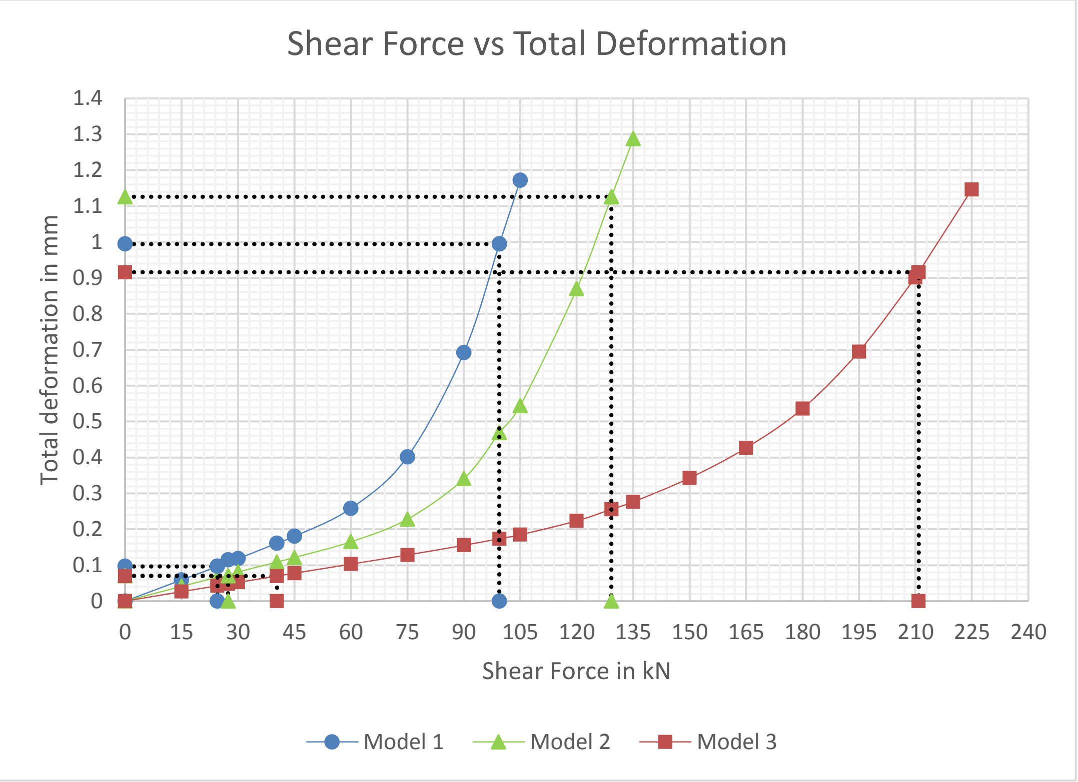
Shear: Equivalent stress (von-Mises) in ANSYS



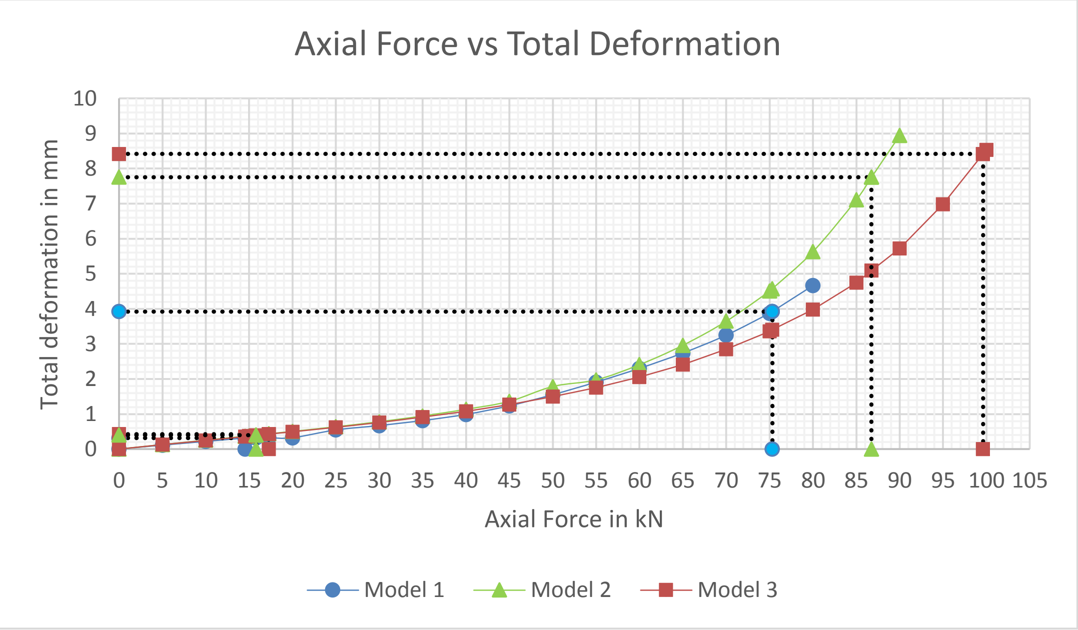
Shear: Support in ANSYS

IV. RESULTS & DISCUSSION:

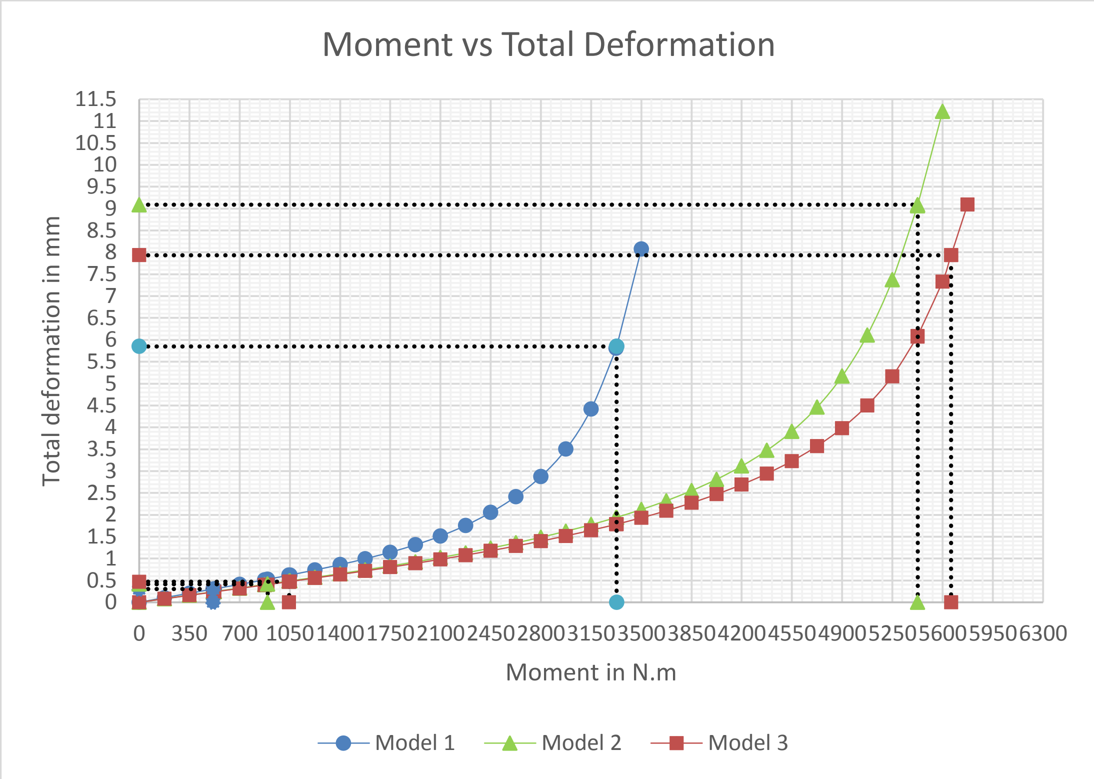
Shear simulation results:



Axial-tension simulation results:



Moment simulation results:



V. DISCUSSION

Concluding statements:

1. The **shear** *yielding* started for model 2 at load which was 11.71% more than that for model 1, while the total deformation of model 2 at that load was 27.14% less than that of model 1. While the yielding of model 3 started at load which was 64.65% more than that for model 1 and 47.39% more than that for model 2. Also the total deformation of model 3 was found to be 27.97% less than that of model 1 and 0.85% less than that of model 2.
2. The *failure* load carrying capacity due to **shear** for model 2 was found to be 29.90% more than that of model 1 while the failure load capacity for model 3 was found to be 112.02% more than that for model 1 and 63.22% more than that for model 2. Also the total deformation of model 2 was found 13.19% more than that of model 1 while the total deformation of model 3 was found 7.94% less than that of model 1 and 18.67% less than that of model 2.
3. *Yielding* due to **axial- tension** started for model 2 at load which was 8.81% more than that for model 1, while the total deformation of model 2 at that load was 26.56% more than that of model 1. While the yielding of model 3 started at load which was 18.79% more than that for model 1 and 9.71% more than that for model 2. Also the total deformation of model 3 was found to be 36.40% more than that of model 1 and 7.77% more than that of model 2.
4. The *failure* load carrying capacity due to **axial-tension** for model 2 was found 15.19% more than that for model 1 while the failure load capacity for model 3 was found 32.28% more than that for model 1 and 14.84% more than that for model 2. Also the total deformation of model 2 was found 97.68% more than that of model 1 while the total deformation of model 3 was 114.60% more than that of model 1 and 8.56% more than that of model 2.
5. Under **moment** loading, *yielding* of model 2 started at load value 65.18% more than that for model 1, while the total deformation of model 2 was 37.45% more than that of model 1. While yielding of model 3 started at load value 102.98% more than that for model 1 and 16.71% more than that for model 2. Also the total deformation of model 3 was 56.26% more than that of model 1 and 13.68% more than that of model 2.
6. The load at which *failure of model 2* occurred under **moment** was 63.06% more than that for model 1, while the failure load capacity of model 3 was 70.07% more than that of model 1 and 4.30% more than that of model 2. Also the total deformation of model 2 was 55.36% more than that of model 1 and the total deformation of model 3 was 35.63% more than that of model 1 and 12.69% less than that of model 2.
7.

VI. CONCLUSION

In this study numerical simulations were carried out to investigate the behavior of interlocking inter-module connections subjected to shear, axial-tension and moment loadings. The model developed previously [Lacey et al] was reviewed and enhanced. Numerical simulations were carried out using ANSYS. Aim of this study was to investigate the effect of the and boundary conditions on the models.

Conclusions:

The main findings are summarized as follows.

1. Under shear type of loading, the model 3 performed considerably better than the model 1 and model 2. This improvement in performance was because of the 4 bolt arrangement which provided greater shear area.
2. Under axial – tension type of loading, the performance of model 3 was again found to be better than the model 1 and model 2. This enhanced performance was because of overall increase in the connection area on account of the 4 bolt arrangement.
3. Under moment type of loading, the performance of model 3 was better than model 1 but was close to that of model 2. So it can be said that increasing the number of bolts doesn't improves the moment capacity significantly but increasing the column section size does improves the moment capacity significantly.
4. The performance of model 3 was significantly better than the model 1 and model 2 under all three types of loadings.

Future Scope:

In the future works the simplified models derived in this study can be applied in the overall numerical simulation of a case study building. In this way, the application of the proposed models will be demonstrated and evaluated for the typical load combinations. Following the numerical case study, the applicability of the simplified models may be verified and extended through further studies on the shear (bearing/yield), axial and moment-rotation behaviours, and the response to combined actions. The application of the simplified models may also be extended by conducting further numerical simulations with different plate thicknesses, column sections, and bolt arrangements.

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