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DEVELOPMENT A HIGH-FIDELITY FINITE ELEMENT MODEL OF A RE-CONSTRUCTIBLE INTER-MODULAR CONNECTION

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Abstract. *This paper outlines the development of a high-fidelity finite element model of a re-constructible inter-modular connection. The proposed inter-modular connection aligns with designing for deconstruction philosophy and aims to enhance speed of volumetric construction while allowing efficient deconstruction at the end of design life. The proposed connection may enable repeated use of high quality prefabricated modular PODS in constructing disaster or emergency shelters in an accelerated timeframe. The high-fidelity finite element model is developed using Component-based Finite Element Method pioneered by IdeaStatiCa®. The modelling approach is verified by comparing the ultimate strength and failure mode derived from the laboratory test of a telescopic square hollow section (SHS) modular connection found in the literature. The step-by-step modelling and verification procedure presented in this study can be used verify other novel connection designs. The verified modelling approach is then used to develop the proposed re-constructible inter-modular connection. The developed model is analysed to determine its design resistance. Stiffness analysis was also conducted to determine the semi-rigidity of the proposed connection. The stiffness information can be used to model these connections as a spring in other macro finite element analysis software such as SpaceGass. The development process of a high-fidelity finite element model of a re-constructible inter-modular connection presented in this paper can enable practicing engineers to develop optimum inter-modular connections for their construction project instead of relying of proprietary modular connections.*

1 INTRODUCTION

Modular construction offers several key advantages: accelerated construction schedules through off-site module production alongside site preparation, cost savings due to standardized designs and factory fabrication, improved on-site safety (with an 80% reduction in accidents), heightened product quality through controlled manufacturing, enhanced productivity via simplified on-site assembly, and environmental benefits, including reduced on-site construction and increased sustainability. Recent years have witnessed significant global research interest in this field [1, 2, 3, 4, 5]

Srisangeerthanan et al. [1] investigated modular structures, particularly multi-story modular buildings (MSMBs), advocating for a fully modular building system, referred to as a complete building system (CBS). The CBS envisions minimal on-site work, limited to foundation, module assembly, and module-to-module interface finishing, upon factory manufacture and module delivery, to create fully complete MSMBs with minimal human intervention. They identified three key components crucial for modular buildings: Gravity Framed Modules (for vertical gravity loads), Lateral Force Resisting System (LFRS) Modules (to resist lateral loads and reduce drift through increased stiffness), and High-Performance Connectors (for proper load transfer both vertically and laterally within the modular structure). Emphasis was placed on the necessity for innovative and robust connector designs to prevent overly conservative or structurally inadequate solutions.

In their comprehensive study, Srisangeerthanan et al. [1] addressed critical challenges in successful modular construction. These challenges encompass module preservation during handling (particularly for both non-structural and structural elements), efficient and cost-effective transportation of off-site constructed modules to the construction site, simple yet robust inter-module connection solutions meeting structural requirements while optimizing efficiency and cost savings, reliable structural systems (especially for lateral load transfer and overall structural robustness, an area with limited research), regulatory issues (including the absence of comprehensive guidelines throughout the structure's lifecycle and a lack of standardized solutions for various critical aspects of modular construction), and design concerns (such as the impact of manufacturing tolerance eccentricities, requiring further research to understand the consequences of minor design variances and the absence of design procedures for non-structural component attachment). The current study focuses on developing a robust inter-module connection facilitating de-construction and re-construction, enabling module reuse with both structural and non-structural elements.

Dai et al. [2] introduced a self-locking plug connection for modular steel construction, suitable for remote assembly. However, disassembly challenges need addressing. Their connection offers automatic assembly, avoids conflicts with structural components, and accommodates various specifications. Sharafi et al. [3] proposed a Modular Integrating System (MIS) with interlocking joints to enhance structural integrity. Finite element modelling and experiments demonstrate the MIS's potential to increase structural integrity and mitigate loss of support. Lacey et al. [4] analysed an interlocking inter-module connection's behavior using numerical and analytical models. Their study highlighted the importance of bolt preloading, shear behavior, and moment-shear interaction. A spring model was proposed to represent semi-rigid connections effectively.

Understanding connection rigidity is vital for semi-rigid connections in modular structures. Yang [5] analysed semi-rigid connections in high-rise steel structures, emphasizing the importance of realistic representation for effective design. While modular construction offers significant advantages, addressing challenges related to re-constructible inter-modular connections and accurately predicting their stiffness requires further research and innovative solutions to enhance performance and sustainability.

Existing research on inter-modular connections primarily relies on complex laboratory experiments, advanced finite element simulations, or a combination of both. Moreover, commercially available inter-modular structures often rely on proprietary connection systems, making it impractical and costly for practicing engineers to design or modify modular structures. The main objective of this paper is to demonstrate the development of a high-fidelity finite element model for inter-modular connections that simplifies disassembly and reassembly. The component-based finite element method employed in this study enables practicing engineers to design and experiment with various inter-modular connections while conducting finite element analyses on the critical design components with ease.

2 COMPONENT-BASED FINITE ELEMENT MODEL [6]

For steel structure design, engineers usually prefer beam members [6]. Nonetheless, certain structural components pose challenges that deviate from conventional member theory. These complexities encompass welded joints, bolted connections, footings, wall openings, variable cross-sectional heights, and point loads. Analysing these components proves intricate due to their non-linear behavior, involving material plasticization, plate contact, and the influence of bolts and welds. Engineering solutions, guided by national codes such as CSN EN1993-1-8 [7] and technical literature, typically adhere to the method of components.

The components method treats joints as interconnected systems, comprising individual components, necessitating a dedicated model for each joint type to assess forces and stresses in each component. While effective, this approach has limitations when dealing with unconventional joint shapes or complex loading conditions [6].

CBFEM (Component-Based Finite Element Model) has been developed collaboratively by IDEA RS, the Department of Steel and Timber Structures at the Faculty of Civil Engineering in Prague, and the Institute of Metal and Timber Structures at the Faculty of Civil Engineering of Brno University of Technology. CBFEM stands out for its generality, simplicity, speed, and comprehensiveness, building upon the strengths of the traditional components method while incorporating finite element analysis [6].

The Finite Element Method (FEM) is a commonly employed technique for structural analysis, showing promise for modelling joints of varying shapes. However, the need for elastic-plastic analysis due to steel's plastic behavior in structures renders linear analysis unsuitable for joint design. FEM models, which employ spatial elements and material properties, prove valuable for studying joint behavior. In CBFEM models, both webs and flanges of connected members are represented as thin plates, benefiting from established solutions [6].

The most challenging aspect of modelling in FEM programs lies in accurately simulating fasteners like bolts and welds. In structural analysis, joints between members are often simplified as massless points where equilibrium equations are assembled. The actual shape of the joint is seldom known within the structural model, with engineers specifying whether the joint is rigid or hinged. A reliable model reflecting the true state of the joint is crucial for accurate design. CBFEM addresses this by utilizing member ends with lengths of 2-3 times the maximal cross-section height, modelling them with plate/wall elements. For greater precision, end forces from 1D members are applied as loads at segment ends and then adjusted to account for the moments they induce [6].

Segment ends at the joint are not inherently connected and require explicit modelling. Manufacturing operations such as cuts, offsets, holes, stiffeners, ribs, end plates, splices, angles, gusset plates, and more are employed in CBFEM to model these connections. Fastening elements like welds and bolts are added to complete the comprehensive joint representation [6].

A significant limitation of the standard Component method pertains to the analysis of internal forces and stresses within a joint. CBFEM replaces the specific analysis of internal forces with general FEA. Specific components such as bolts or welds continue to be analysed according to the standard Component method [6]. Nevertheless, special FEM components are developed to accurately model the behavior of welds and bolts within the joint. In CBFEM, all parts of 1D members and additional plates are modelled as plate/walls, and the material behavior is represented using an ideal plastic material for design purposes.

Meshes of plates/walls are not merged, and no intersections are generated between them, in contrast to typical modelling approaches. Special massless force interpolation constraints are added between meshes to ensure the connection between adjacent plates, providing excellent results in terms of precision and analysis speed. This patented method models welds using a special elastoplastic element. Bolted connections, consisting of clasped plates and bolts, are represented with contact elements that act in compression only, with shear forces carried by bearing [6].

3 CODE-BASED CONNECTION COMPONENT DESIGN

IdeaStatiCa® employs code based standard Component method to analyse specific components such as bolts or welds. Following section summarizes the Australian standard-based equations used to design the welds and bolted connections in this study.

3.1 Weld design

3.1.1 Fillet welds

The resistance of fillet weld is determined according to AS 4100-2020 [8] – Cl. 9.6.3.10 (Eq. 1). Plastic redistribution in weld material is applied in Finite Element Modelling. The most stressed element is checked.

$$\phi V_w = \phi 0.6 f_{uw} t_t \tag{1}$$

where, V_w^* refers to design force per unit length of weld, t_t represents throat thickness, f_{uw} denotes nominal tensile strength of weld metal. $\phi_w = 0.8$ signifies resistance factor for welded connections.

3.1.2 Butt welds

The resistance of butt weld is assumed as that of the base metal and is not checked.

3.2 Bolt Design

The tensile resistance of a bolt is assessed according to AS 4100-2020 – Cl. 9.2.2.2 (Eq. 2). The shear resistance of a bolt is assessed according to AS 4100-2020 – Cl. 9.2.2.1 (Eq. 3). Each shear plane of a bolt is checked separately. When the bolt threads are intercepted by a shear plane, the minor diameter area of the bolt is used instead of nominal plain shank area of the bolt. The resistance of a bolt loaded by combined tension and shear is assessed according to AS 4100-2020 – Cl. 9.2.2.3.

$$\phi N_{tf} = \phi A_s f_{uf} = 104.2 \text{ kN} \geq N_{tf}^* = 0.1 \text{ kN} \tag{2}$$

$$\phi V_f = \phi 0.61 f_{uf} A_o = 82.7 \text{ kN} \geq V_f^* = 0.2 \text{ kN} \tag{3}$$

where, A_s refers to tensile stress area, A_o implies nominal plani shank area of the bolt f_{uf} signifies minimum tensile strength of the bolt and $\phi_b = 0.8$ refers to resistance factor for bolted connections.

The slip resistance of a bolted joint is assessed according to AS 4100-2020 – Cl. 9.2.3 (Eq. 4).

$$\phi_{sf} V_{sf} = \phi_{sf} \mu N_{ti} k_h \tag{4}$$

where, $\mu = 0.35$ refers to Slip factor, N_{ti} represents minimum bolt tension at installation, k_h denotes a factor for different hole types, ϕ_{sf} signifies resistance factor for slip ciritcal bolted connections.

3.3 Ply in bearing

The resistance developed at the bolt in a bolted joint subjected to bearing and shear is assessed according to AS 4100-2020 – Cl. 9.2.2.4 (Eq. 5 and 6).

$$V_b = 3.2 d_f t_p f_{up} \tag{5}$$

$$\phi_b V_b = 0.9 V_b \tag{6}$$

where, d_f diameter of a bolt, t_p thickness of a plate, f_{up} tensile strength of the ply, $\phi_b = 0.9$ resistance factor for bearing of bolt holes, a_e minimum distance from the edge of a hole to the edge of a ply.

3.4 Tension and shear interaction

Interaction of tensile and shear forces is assessed according to AS 5216:2018 [9] – Cl. 8 (Eq. 7). The steel interaction resistance of the fastener is based on AS 4100 [8].

$$\left(\frac{V_f^*}{\phi V_r}\right)^2 + \left(\frac{N_{tf}^*}{\phi N_{tf}}\right)^2 = 0 \tag{7}$$

Where, V_f^* represents design shear force of the bolt, ϕV_r denotes the lowest shear deisgn strength determined from all appropriate failure modes, N_{tf}^* refers to design tensile force of the bolt, ϕN_{tf} signifies the lowest tensile design strength determined from all appropriate failure modes.

4 MODELIING METHODOLOGY

4.1 Simplified modular structure

The application of the simplified modular structure in this study is focused on temporary disaster housing. It was chosen due to its potential for easy disassembly, suitability for rapid assembly in remote areas, and ease of analysis, making it a valuable solution for swift disaster relief efforts. The structural dimensions and assumptions for the analysis were carefully selected to replicate connection behavior. The modular structure aims to address disaster relief scenarios and the potential for the quick assembly of apartment blocks. The generic structure consists of modules measuring 2.5m in width, 2.5m in height, and 6m in length, providing comfortable accommodation for 4-6 people in a self-sufficient unit. The design allows for the assembly of multiple modules into larger shelters. The final model is an eight-module structure, measuring 5m in width, 12m in depth, and 5m in height, offering flexibility for analysing various connection positions and supporting multi-storey disaster relief shelters.

This design opens possibilities for multi-storey disaster relief structures, especially in space-constrained situations. The selected inter-modular connection is an interior edge connection, as highlighted in Figure 1.

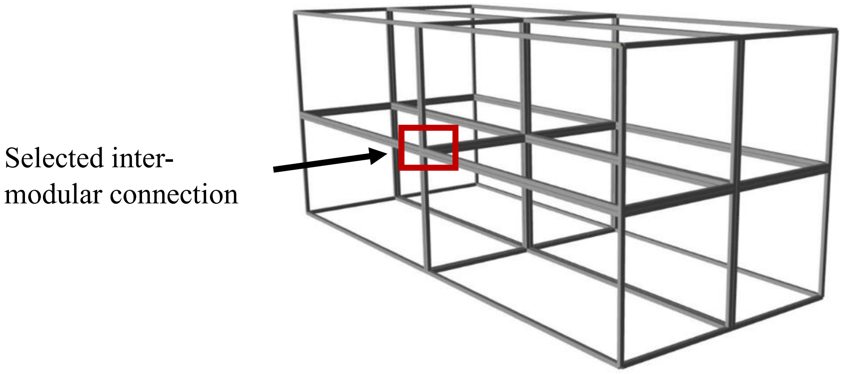

Figure 1: Simplified Modular Structure

4.2 Modelling using IdeaStatiCa®

IdeaStatiCa® [6] is user-friendly software that preserves traditional FEA modelling principles while enhancing complex modelling processes with built-in calculation codes, modelling tools, error detectors, and report generators. These features assist practicing engineers in quickly and efficiently acquiring crucial design data. The following section of this paper elaborates on the modelling methodology through a preliminary deconstructable connection design of an exterior edge connection, which will enable connecting four modules at one exterior edge. The primary innovation revolves around the utilization of blind bolts, which facilitate ease of construction, deconstruction, and reconstruction with minimal access. Detailed description and dimensions of the design are provided by Roufogalis [10].

4.2.1 New project creation, design standards, code, and calculation settings

In the initial stage of a new project design, IdeaStatiCa® offers the option to configure design standards, code specifications, and calculation settings. For this project, the design adheres to the Australian design code (AS 4100 [8]), and the default material for the design project is set to 300 PLUS. IdeaStatiCa® provides two options for new connection designs: one involves utilizing the typical connection database, while the other entails generating a blank design.

Table 1: Code settings

Item	Value	Unit	Reference
Coefficient of friction between steel and concrete	0.55	-	
Slip factor in friction-type connections	0.35	-	AS 4100:2020 – 9.2.3.2
Limit plastic strain	0.05	-	
Detailing	Yes		
Minimum bolt pitch [d]	2.50	-	AS 4100:2020 – 9.5.1
Minimum edge distance to a bolt [d]	1.25	-	AS 4100:2020 – 9.5.2
Local deformation check	Yes		
Local deformation limit	0.03	-	CIDECT DG 1, 3 - 1.1
Geometrical nonlinearity (GMNA)	Yes		Analysis with large deformations for hollow section joints

4.2.2 Connection modelling

For this study, a simple T-shape connection was chosen as the basis for the design. A member was removed, and the section geometry was altered to 89x89x6. Additional components were incorporated into the connection model using the 'New member' and 'add operations' functions. Specifically, for this model, an 89x89x6 mm SHS section, a 75x75x5 mm SHS section, and a middle plate of 190x89x8 mm were added via a stiffener plate. The plate stiffener was introduced, followed by the addition of a second member, offsetting by 43mm in each direction. Two members were added on opposite sides of the stiffener, connected with welds. Furthermore, an additional smaller section was inserted inside the original Square Hollow Section. The mid-plate was offset so that its surface contacted the bottom of the 75x75x5 SHS and the 89x89x6 SHS, forming the overall shape of the connection. The outer 89x89x6 SHS and inner 75x75x5 SHS sections have two contacting surfaces, one of which is connected using two Blind bolts. To generate the bolts, the 'Operation' button was used, and M16 HR8.8 bolts were added at 30 and 80 millimetres on web 1 of each 89x89x6 mm and 75x75x5 mm SHS member. Welds can also be applied using the same option between the inner section and the mid-plate. Additionally, a horizontal SHS section was added to the outermost telescopic section to represent the beams of the module.

Figures 2-4 display snapshots of different stages of the modelling process. Detailed modelling steps are presented in Ferguson's work [11].

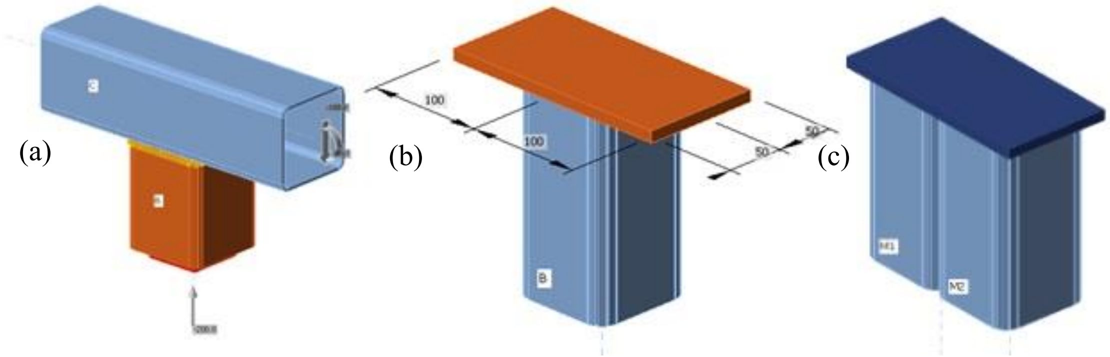

Figure 2: (a) base model (b) Stiffener plate addition (c) addition of a member using offset method

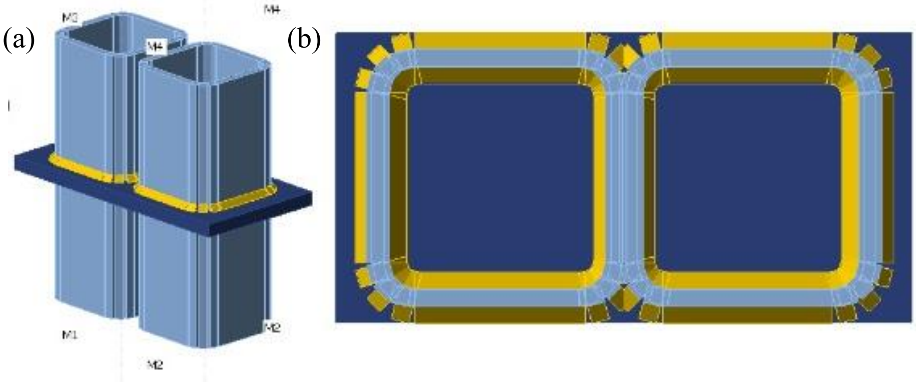

Figure 3: (a) addition of weld (b) weld details

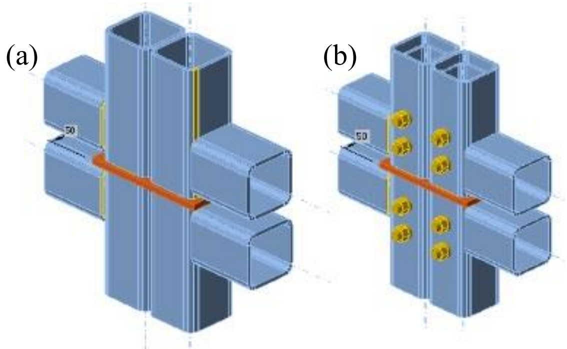

Figure 4: (a) addition of beams (b) final model with inner SHS sections and bolts

4.2.3 Load application

The next step is to apply loads to analyse the performance of the connection. Loads can be applied with a specific value or as a percentage of the capacity of the member's cross-section, serving as a simplified tool. However, it is recommended to use the 'load in equilibrium' option for all load cases.

5 RESULTS AND DISCUSSIONS

5.1 Verification model

The inter-modular connection developed by Gunawardena [12] was employed for verification purposes. Figure 5 illustrates the inter-modular connection model that

Gunawardena [12] developed and tested. Figure 6 displays the equivalent model created using IdeaStatiCa®. The model underwent verification against joint capacities under in-plane shear load, including slip critical and ultimate bolt capacity, as well as failure mode analysis. The equivalent stress (Von-Mises) contour was also examined to ensure the model's expected behavior. Table 2 and Figure 7 provide a comparison between the results obtained in the present study and those obtained or calculated by Gunawardena [12]. Notably, the predicted slip resistance significantly differs due to the applied bolt pre-tension of 59.2 kN, which is considerably smaller than the minimum bolt tension of 95 kN recommended during installation according to AS4100 [8].

Table 2: Summary of verification analysis

Verification criteria	Gunawardena [12]	Present study
Verification model – (Slip critical) in-plane shear	83.5 kN	128 kN
Verification model – (Bolt under shear) in-plane shear	398.9 kN	410.8 kN
Failure mode	Bolt failure	Bolt failure
Stress distribution	Focused on bolts only	Members within yield limit

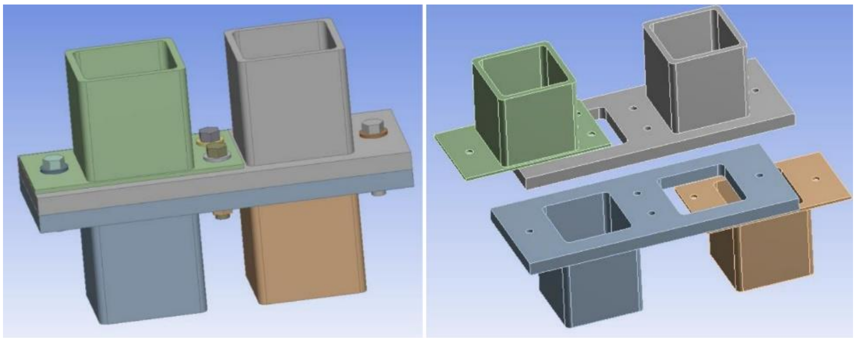

Figure 5: The model developed and tested by Gunawardena [12]

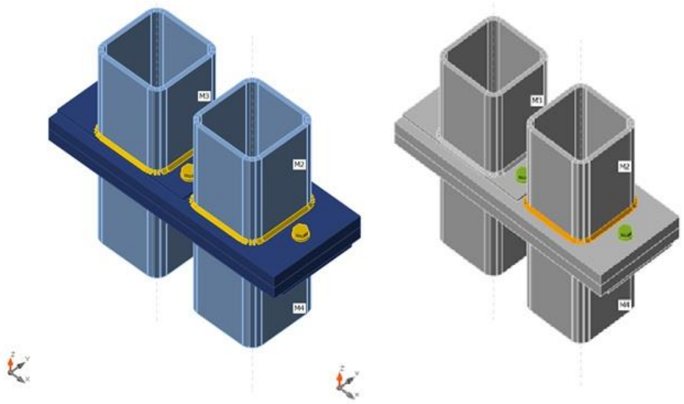

Figure 6: Verification Model

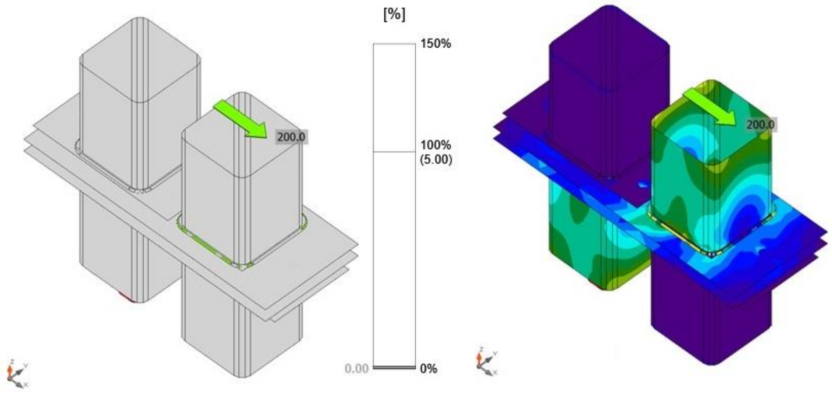

Figure 7: Equivalent strain (left) and equivalent stress (right) diagram of the verification model

The verified model is subsequently employed to establish the Joint design resistance curve. This curve presents the results as a percentage of the applied load (200 kN). It indicates that the joint can withstand an in-plane shear load of 328.6 kN with 1% plastic deformation. It is important to note that the design resistance of 328.6 includes a 0.8 resistance factor. Therefore, this value was divided by 0.8 to determine the actual resistance of the joint, which is 410.8 kN (as shown in Table 2).

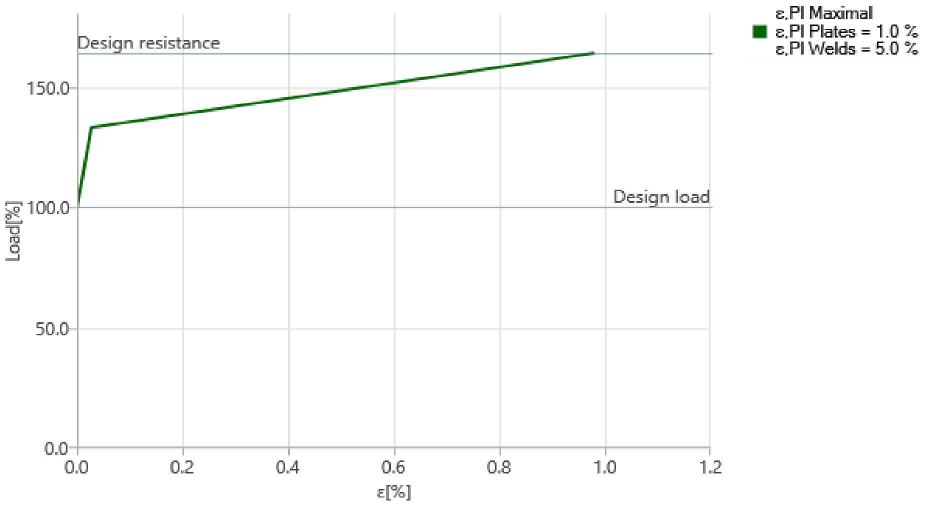

Figure 8: Joint design resistance (verification model)

Table 3: Joint design resistance

Analysed Model	Design Resistance (kN)
Verification model – (Slip critical) in-plane shear	328.6
Verification model – (Bolt under shear) in-plane shear	89.6
Proposed model - in-plane shear	48.1

The verified model was then loaded under in-plane moment (IP-M) and out-of-plane Moment (OP-M) at one of the columns to determine its stiffness properties. Tables 4 and 5 show the rotational and secant stiffness and joint class information, respectively, where $M_{j,Rd}$ refers to Bending resistance, $S_{j,ini}$ represents Initial rotational stiffness, $S_{j,s}$ denotes Secant rotational stiffness, ϕ signifies Rotational deformation, ϕ_C indicates Rotational capacity, $S_{j,R}$ means Limit value – rigid joint, $S_{j,P}$ refers to Limit value - nominally pinned joint, calculated based on Chapter 5 of Eurocode EN 1993-1-8:2005 [7]. L refers to the storey height of the column. Figure 9 shows the moment rotation diagram for the verification joint.

Table 4: Rotational stiffness

Model	Comp.	Mj,Rd [kNm]	Sj,ini [MNm/rad]	Φc [mrad]	L [m]	Sj,R [MNm/rad]	Sj,P [MNm/rad]	Class.
Verification	IP-M	4.2	1.0	4.9	3.20	20.2	2.0	Pinned
Verification	OP-M	5.7	1.9	3.5	3.20	20.2	2.0	Pinned
Proposed	IP-M	0.0	∞	0.0	3.20	2.7	0.3	Rigid
Proposed	OP-M	0.0	∞	0.0	3.20	2.7	0.3	Rigid

Table 5: Secant rotational stiffness

Name	Comp.	M [kNm]	Sjs [MNm/rad]	Φ [mrad]
Verification	IP-M	10.0	0.3	33.0
Verification	OP-M	10.0	0	8.6

Proposed	IP-M	8.6	∞	0.3
Proposed	OP-M	8.6	∞	0.2

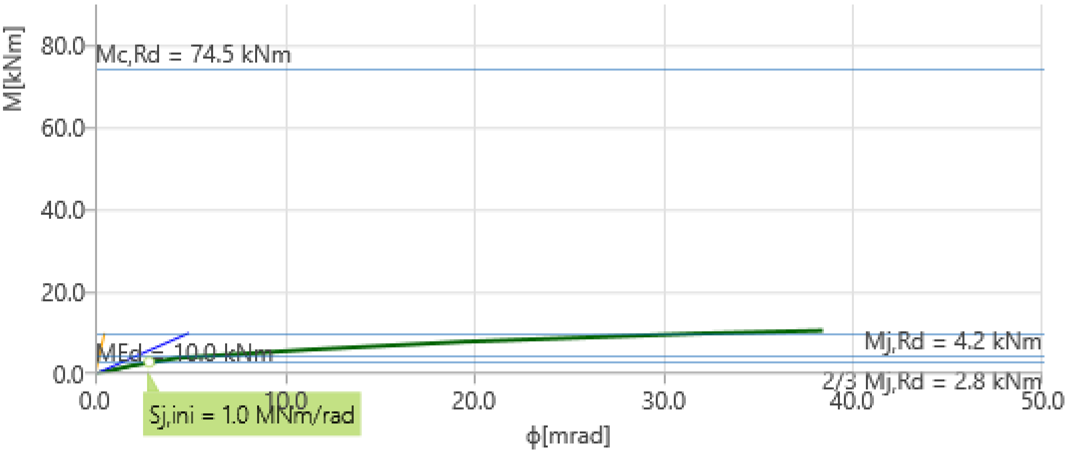

Figure 9: Moment-rotation diagram

5.2 Preliminary deconstructable connection model

This section presents the analysis results for the proposed inter-modular connection. Figure 10 shows the equivalent strain diagram, followed by equivalent stress contours in Figure 11. Figure 12 displays the joint design resistance, and Figure 13 illustrates the moment-rotation diagram. Tables 3, 4, and 5 provide information regarding the design resistance, rotational stiffness, and secant stiffness of the proposed model.

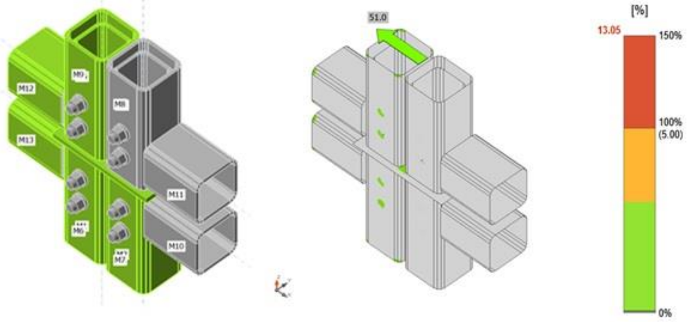

Figure 10: Equivalent strain diagram

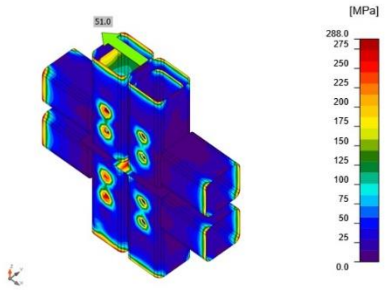

Figure 11: Equivalent stress diagram

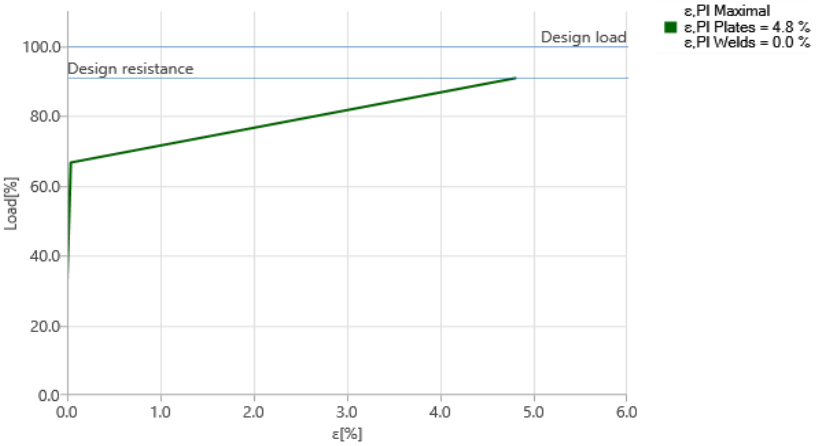

Figure 12: Joint design resistance (proposed model)

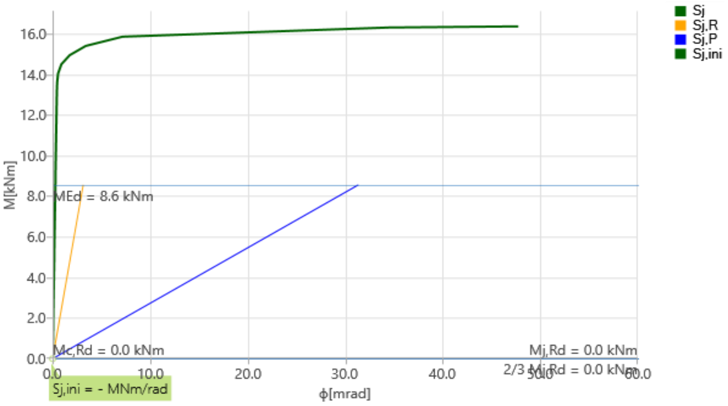

Figure 13: Moment-rotation diagram (proposed model)

5.3 Additional capabilities – manufacturing operations

Tables 6 and 7 showcase an additional feature of IdeaStatiCa®. Users have the capability to extract detailed manufacturing operations required to prepare the connection, which can assist laboratory staff in efficiently preparing the connection for testing. For practicing engineers, this feature enables them to estimate the approximate cost of producing each connection.

Table 6: Manufacturing operations for the designed inter-modular connection

Name	Nr.	Welds [mm]	Length [mm]
SP1	1		
CUT1		Double fillet: a = 4.2	254.5
CUT2		Double fillet: a = 4.2	254.5
CUT3		Double fillet: a = 4.2	254.5
CUT4		Double fillet: a = 4.2	254.5
CUT5		Butt: a = 6.0	310.5
CUT6		Butt: a = 6.0	310.5
CUT7		Butt: a = 6.0	310.5
CUT8		Butt: a = 6.0	310.5
CUT9		Butt: a = 6.0	310.5
CUT10		Butt: a = 6.0	310.5
CUT11		Butt: a = 6.0	310.5
CUT12		Butt: a = 6.0	310.5

Table 7: Manufacturing details for the welds

Type	Material	Throat thickness [mm]	Leg size [mm]	Length [mm]
Double fillet	490 MPa	4.2	6.0	1018.2
Butt	490 MPa	-	-	2484.3

6 LIMITATIONS AND ADVANTAGES OF IdeaStatiCa®

Some limitations of IdeaStatiCa® include the use of an elastic fully plastic material model, the absence of bolt deformation analysis, unavailability of stiffness calculation under shear load, and the inability to model the impact of bolt hole clearance. On the other hand, its advantages encompass cost calculation, the ability to model manufacturing operations, and a high-fidelity finite element model that integrates design elements, allowing for efficient modelling and variation of bolts and welds. This stands in contrast to general-purpose finite element analysis software like ABAQUS.

7 CONCLUSIONS

Modular construction offers significant benefits but faces challenges in developing re-constructible inter-modular connections and accurately predicting their stiffness. This paper presents a high-fidelity finite element model for such connections, utilizing IdeaStatiCa®'s component-based finite element approach. It serves as a demonstrative showcase of a high-fidelity finite element model for an inter-modular connection designed to facilitate disassembly and reassembly in modular construction. Leveraging the component-based finite element modelling approach pioneered by IdeaStatiCa®, this study developed two distinct models: one for verification against existing test data found in the literature and another for the preliminary analysis of our proposed dis-connectible connection. This paper presents findings related to joint resistance, rotational behavior, and secant stiffness obtained from these two models.

The process adopted in this study can assist practicing engineers in utilizing published experiments and advanced finite element analysis data to develop their own inter-modular connection designs. Additionally, it can help researchers align their innovations with existing design standards, thus facilitating the integration of new ideas into practical inter-modular connection design.

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