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NUMERICAL ANALYSIS ON A REVERSIBLE CONNECTION FOR STEEL MODULAR BUILDINGS

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Abstract

Modular buildings are a new type of structural system composed by prefabricated modular units and assembled on site through inter-modular connections. These structures can form complete building blocks with suspended ceilings and installations, including electrical and water systems. These modular solutions can be adapted to any use like hospitals, housing schools, etc.

This work focuses on the analysis of structural behavior on a reversible steel connection modelling with finite element approach.

To this scope, in the paper an ideal case study is considered, characterized by steel elements. The modules are assembled by inter-module connections that allow for rapid assembly on-site, without any need of skilled workmanship reducing the welding and the use of bolts. Therefore, Midas Fea NX is used to define the contact between steel elements in detail.

Keywords: Green design, modular constructions, reversible connection, seismic analysis, steel connections.

1 INTRODUCTION

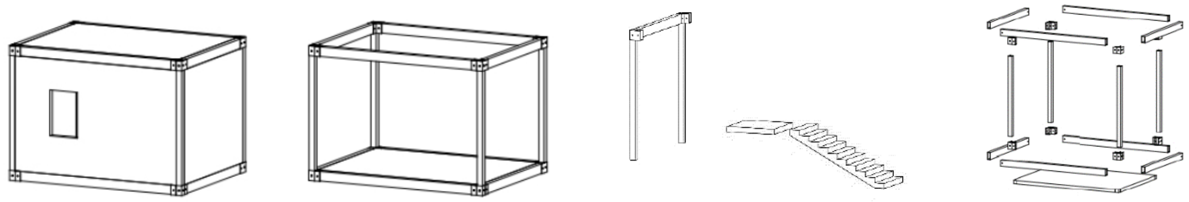
The use of the term "modular construction" refers to a method of building structural elements according to which they are manufactured by industrial processes and assembled on site. Use of modular structures dates to the end of the 1990s and has evolved significantly to play an important role in the construction industry worldwide. Major applications have occurred in the construction of hotels, residential apartments, school buildings, temporary post-catastrophe housing, and military operations. This development is mainly due to the main benefits such solutions have. In particular, the cost of designing and building a structure using modules is generally lower than the conventional method; design, construction and installation of the various modules are much quicker than the equivalent cast-in-place solution and therefore there is a saving in terms of time as well; there is a saving in terms of waste produced since building the individual modules in-house results in waste production that is significantly inferior to conventional construction techniques.

Modular steel buildings can be divided, depending on the structural system, into different types, including entirely modular structures and hybrid structures. The first concerns individual modular units linked together and made integral through connections. The second combines modules assembled with a primary structure made of steel or reinforced concrete, so as to improve resistance for gravitational loads.

This paper will discuss the first type mentioned earlier and referred to as a Modular Functional Unit (MFU). The structure of which the individual modules are composed is called Modular Structural Units (MSU), and the individual structural components are called Elementary Structural Units (ESU), Figure 1.

The ESUs, that are part of the steel structure, are held together through steel connections, which is also an important structural element for the purpose of absorbing seismic action. In modular buildings, connections can be regrouped into inter-modular, intra-modular and module-foundation buildings.

The work presented is part of an on-going research project [1] aimed at proposing reference for modules, suitable for seismic zones and characterized by low seismic damage. In particular, the focus is on inter-modular connections.



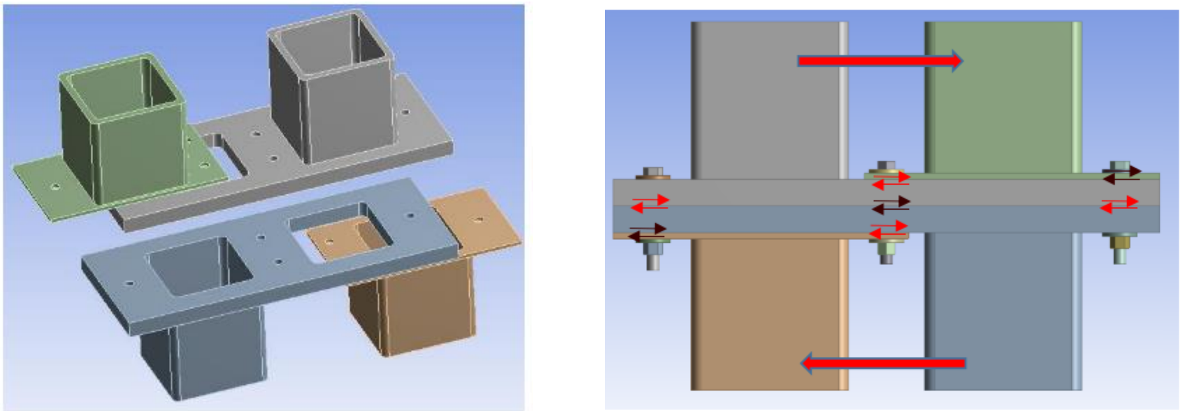
a) b) c) d)

Figure 1: a) Modular Functional Unit (MFU); b) Modular Structural Units (MSU); c) Elementary Structural Unit (ESU); c) Elementary Structural Component (ESC).

2 STATE OF ART

The work focuses on inter-modular connections. This type of connection must be able to assure horizontal connection between adjacent modules and vertical connection between piled modules. The need to connect modules vertically often finds difficulties because it is necessary to provide a gap between the floor and ceiling beams that allows access to the connections from the outside and the passage of services between the beams. Different solutions can be found in the literature, and a few are shown thereafter.

The first example of connection considered is analyzed by T. Gunawardena [2]. This connection is designed to connect the modules both horizontally and vertically and transfer their actions in both directions. The connection consists of four different plates, each welded to the hollow columns Figure 2a. Only two of these horizontally cover the entire connection. The plates are connected through bolts, with the center bolts spanning three shear zones and the bolts placed in the two lateral zones (Figure 2b). The horizontal plates cause creep failure in the presence of horizontal forces, such as those that can occur in earthquakes.



a) b)

Figure 2: Modular connection: a) components; b) existing shear planes in the connection when column is axially loaded (T. Gunawardena [2])

Another example is presented by Z. Chen et al. [3] in two different versions shown in Figure 3. Both versions have a plug-in device to transfer horizontal loads and a beam-to-beam bolt as the vertical connection. The difference between the two solutions is the presence of a stiffener in the weld zone between the column and the beam (element 9 on the right of Figure 3). Of these two proposals, in addition to analysis through Finite Element software, experimental tests have been carried out. The experimental results show that the connections, subjected to static loading failed with fracture in the unit joint welds. The diagonal stiffeners effectively strengthen the connection in the unitary joint.

However, the connection in reference possesses significant post-serving deformation capacity and ductility.

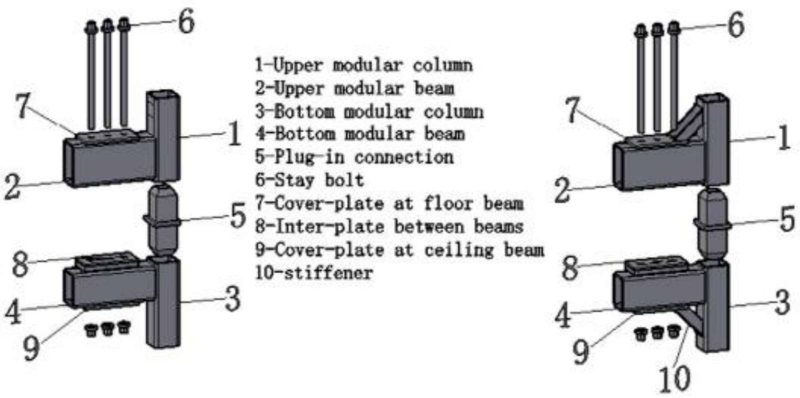


Figure 3: Z. Modular Connections (Chen et al. [3])

3 INTER-MODULE CONNECTION PROPOSED

Starting from the state of the art and analyzing some of the connections, the following study presents a first part of the design of an inter-modular connection that can minimize the use of bolts and avoid sliding between its components. The connection consists of tubular columns joined through a connection plug-in. A u-shaped profile is welded to the columns, on which the beam is placed. The two elements are fixed through a single pin (Figure 4a). This connection can also be used to connect 4 or 8 modules (Figure 4c). For this study, the simplest case is considered: two columns and one beam that are part of a MFU (Figure 5) consisting of structural elements described in Table 1.

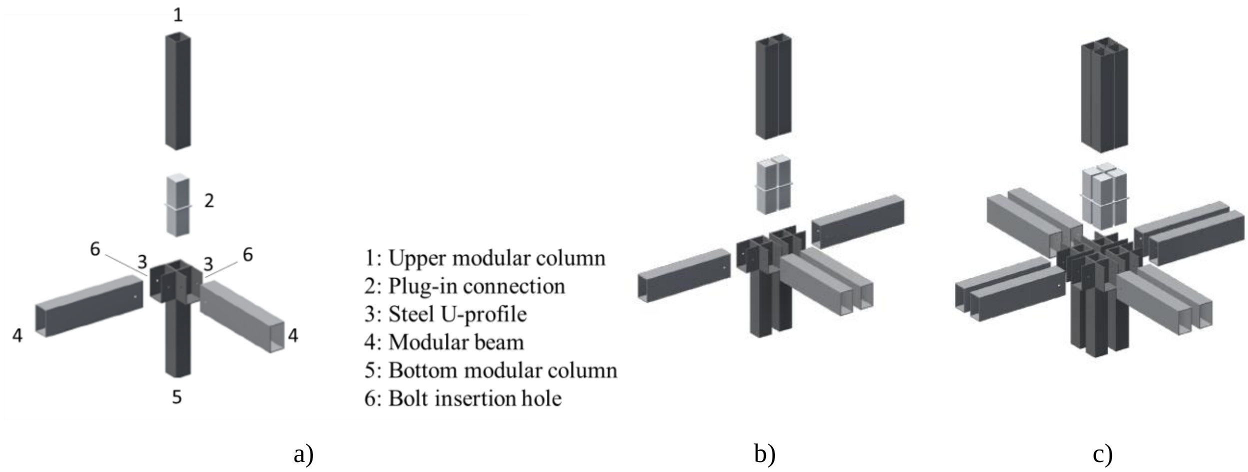


Figure 4: Proposal inter-module connection

Element	Width (mm)	Height (mm)	Thickness (mm)	Length (mm)
Beam	150	250	8	1000
Column (Upper and Bottom)	150	150	8	1000
Plug-in (Upper and bottom)	134	134	8	250
Plate	166	166	8	-

Table 1: Characteristics of structural element

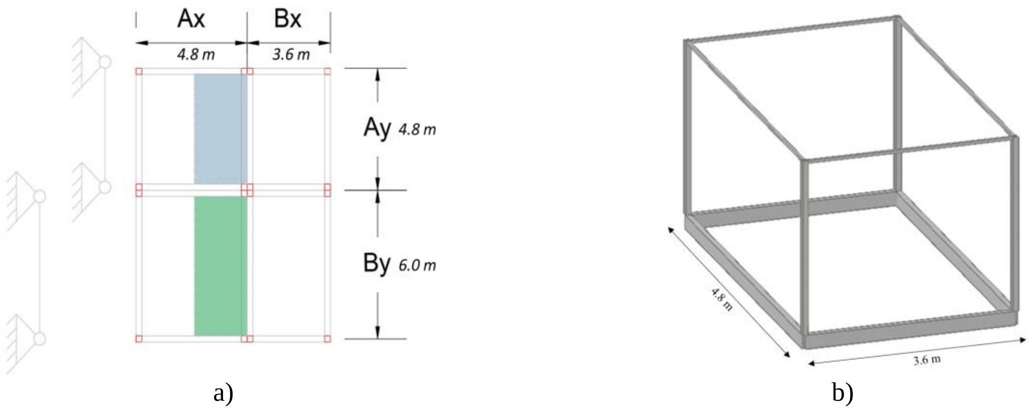


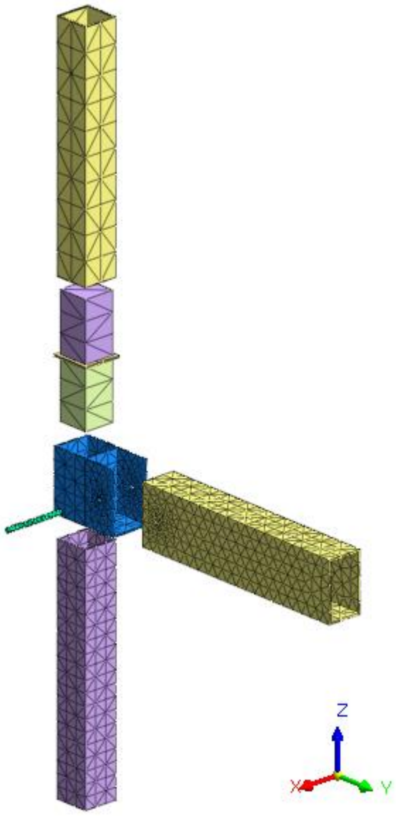
Figure 5: MFU dimensions.

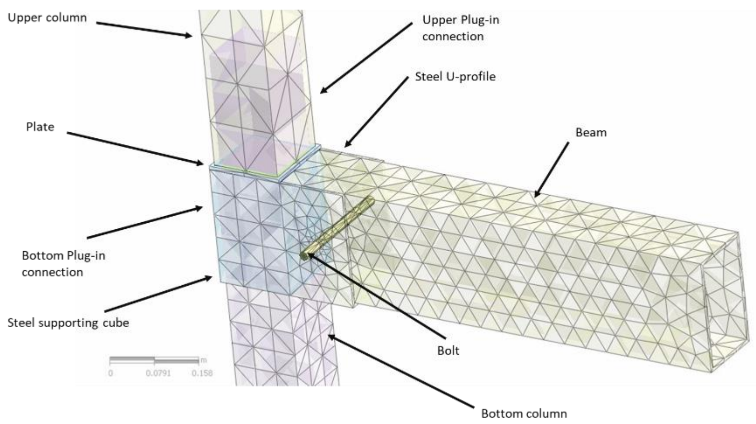
3.1 Numerical modelling

Modeling of the connection is conducted through Midas FEA NX 2023 v.1.1 using solid elements. During this type of modeling, it is important to define the contact between the individual elements that make up the connection. In fact, contact conditions are applied to the meshes of the solid elements (visible in exploded view in Figure 6a) according to their real condition (Figure 6b). The software presents 4 contact types described in detail in Table 1 [4] [5]. For the present study, three contacts are mainly used, welded contact and rough contact. The first one is used between the welded surfaces and that therefore the load distribution does not vary as the mesh changes because the faces are completely joined; the second considers the impact between the solids preventing penetration; the third considers the sliding between two surfaces.

All elements are in steel and they are defined through a bilinear isotropic bond considering Von Mises plasticity. The material considered is Fe510 steel with a modulus of elasticity of 206 GPa and Poisson's ratio 0.3, according to EN 10025-2:2019 [7]).

The maximum horizontal displacement is equal to 20 mm (corresponding to drift 1%) in Y-direction, and it is applied at the top of the upper column. The sub-assemblage considered in this studied reproduces a beam-column joint between two consecutive steel modules. Therefore, in order to better investigate the joint behavior under static lateral loads the numerical model has a hinge at the base of the lower column and at the end of the horizontal beam. In order to permit horizontal displacement of the beam the hinged end has the possibility as well of moving horizontally. Pushover nonlinear analyses have been performed. For simplicity in this study no axial load has been applied at the top of the column.





Element	Contact Type
Upper column – upper plug-in connection	IV
Upper plug-in connection - plate	I
Plate – bottom plug-in connection	I
Bottom plug-in connection – bottom column	IV
Steel u-profile – steel supporting cube	I
Steel supporting cube – bottom column	I
Beam – steel u-profile	II
Beam – steel supporting cube	IV
Bolt – steel u-profile	IV

a) b)

Figure 6: a) exploded view of beam, columns and their connections; b) contact types used in the study.

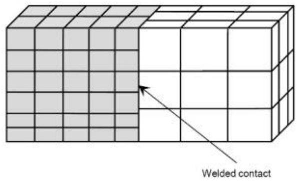
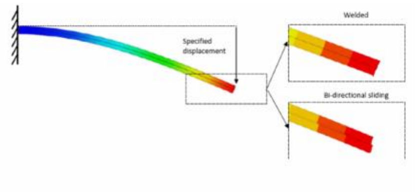
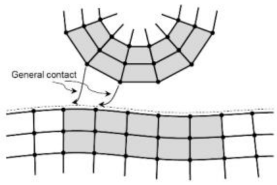
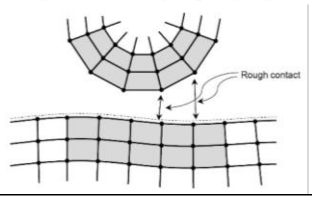
Type	Typology	Description	Graphic description
Type I	Linear	Welded contact: This is a type of contact who considers at the start of the analysis the welded between two objects.	
Type II	Linear	Bi-directional sliding contact: it considers only the slidings.	
Type III	Non Linear	General contact: this contact considers the impact and friction between two objects not in contact at the start of the analysis.	
Type IV	Non Linear	Rough contact: This type of contact considers only the impact. It does not consider sliding between two faces.	

Table 2: Different type of contact in Midas Fea NX [4], [5].

4. RESULTS

The maximum force applied at the head node of the upper column can be read in the force-displacement graph shown in Figure 7.

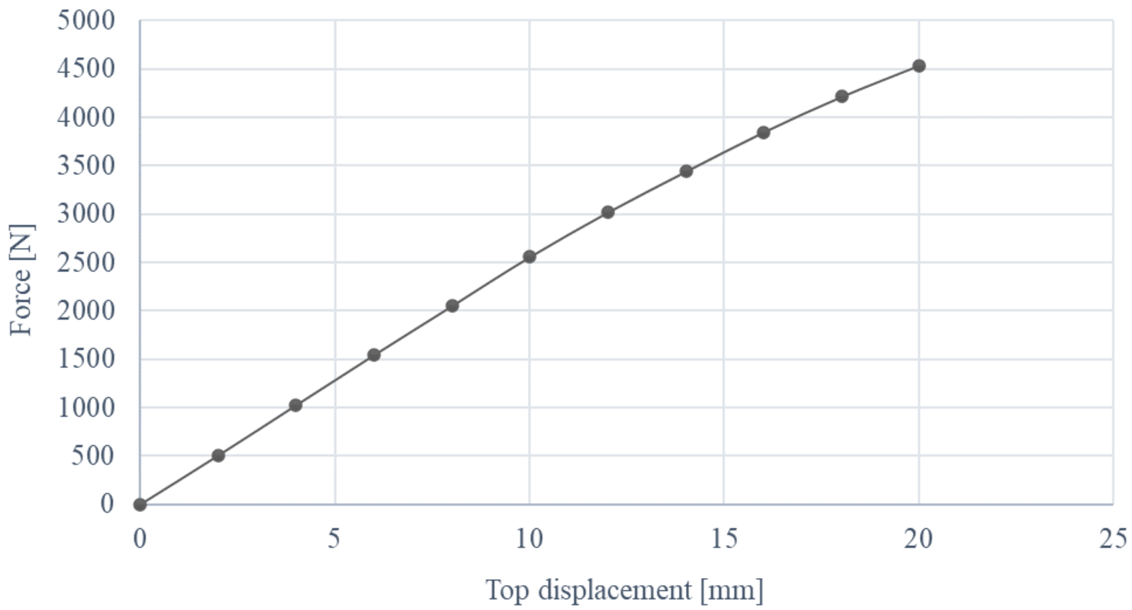
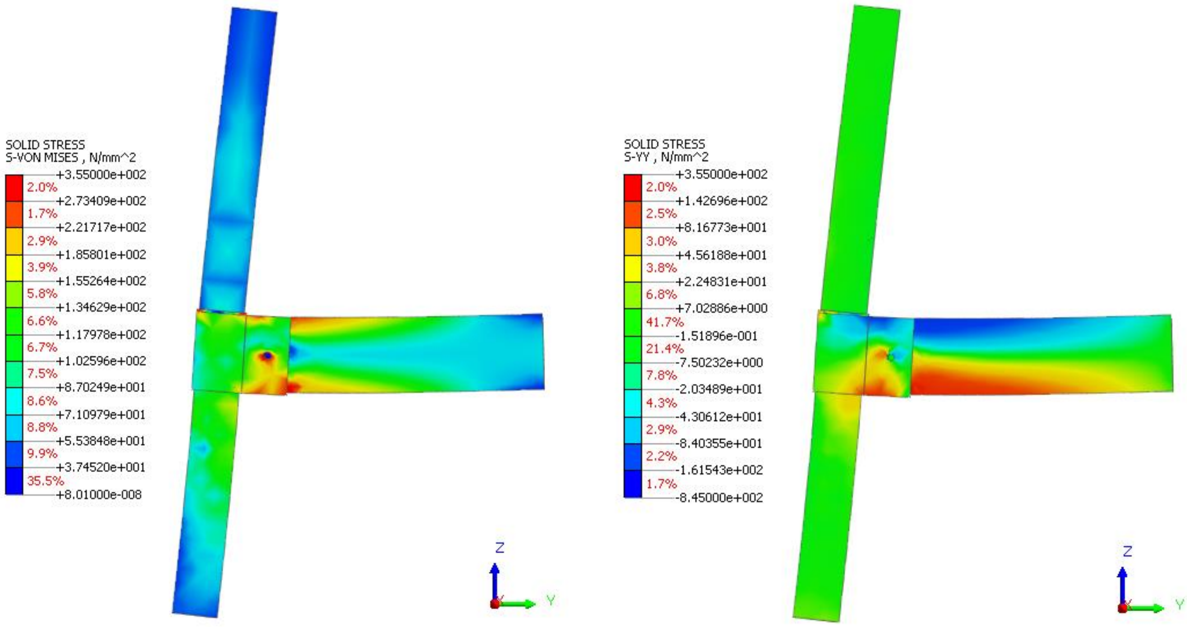


Figure 7: Force-displacement graph.

The Figure 8a shows the Von Mises stress results accounting for all possible combinations of stresses present in the analysis model. The Figure 8b shows the stress distribution in Y-direction where, areas subjected to compression are visible in blue while areas subject to tension are in red.



a) b)

Figure 8: a) Von Mises stress distribution; b) Y- direction stress distribution.

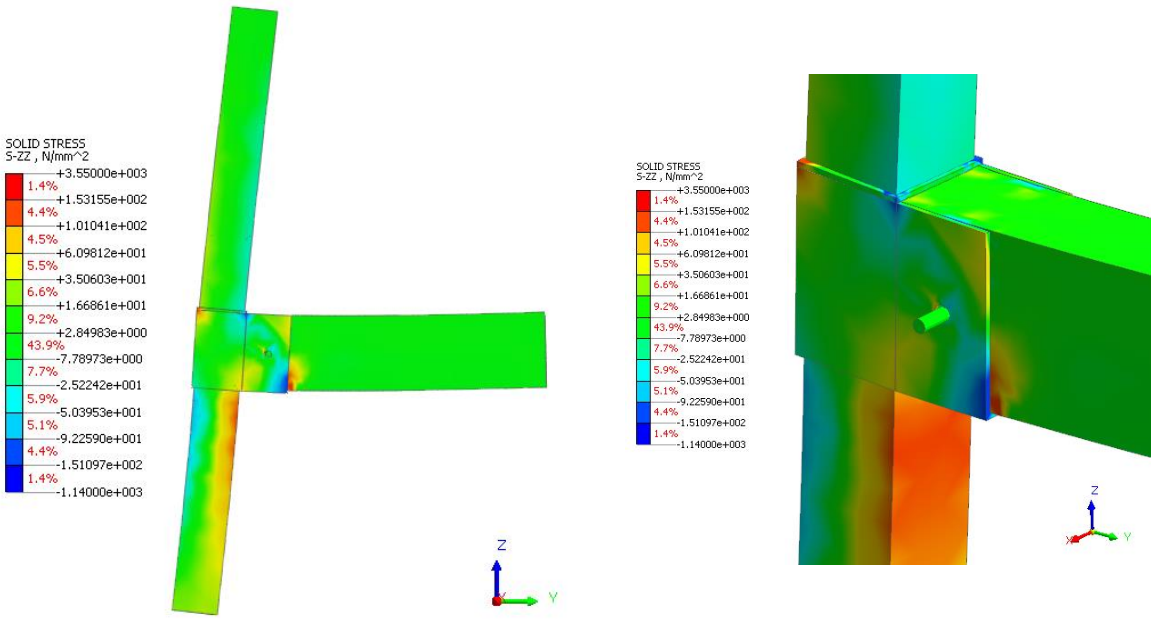
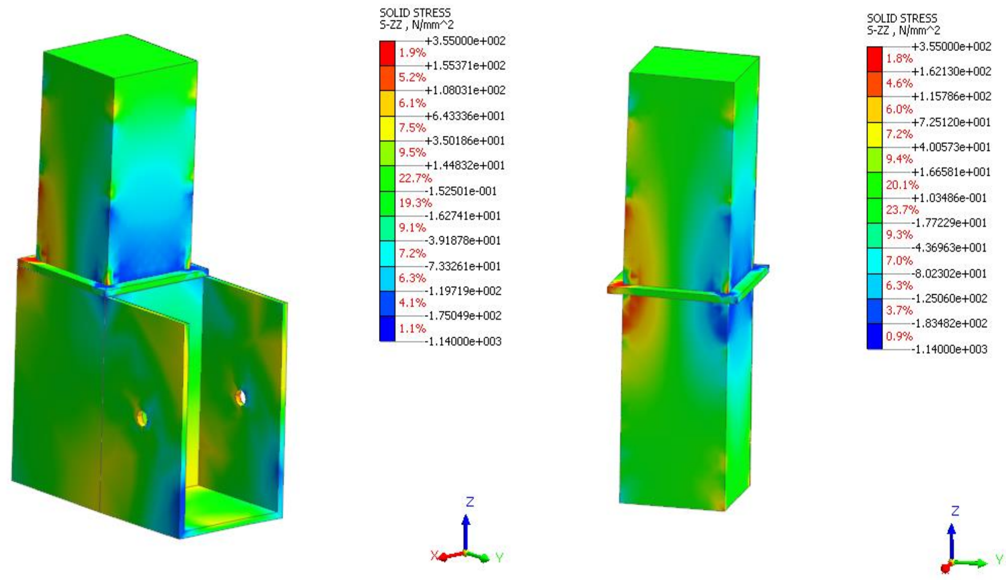


Figure 9: Z – direction stress distribution.

The stress state in the Z-direction shows that higher stress states occur near the welding, as visible in Figure 9 and in Figure 10.

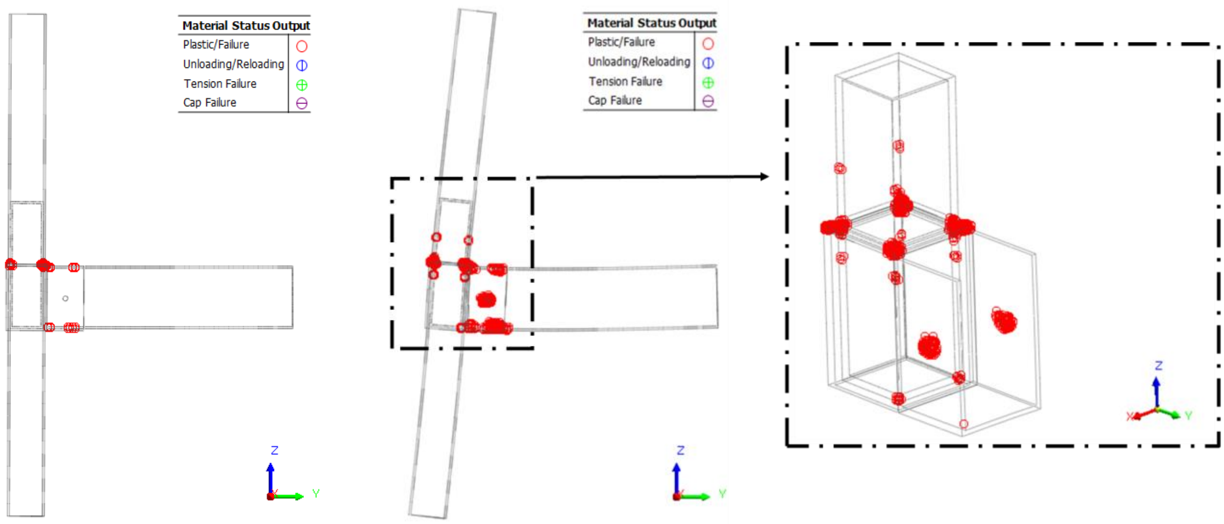
In Figure 11 the plastic state of the elements is observed. Specifically, Figure 11a shows the state of plasticization at the first steps of analysis, and Figure 11b shows the final plastic state. The areas principally affected by material plasticization are the u-profile, the connection (plug-ins and connection plate), and the connection cube.

The graph in Figure 12 shows the maximum yield stress for element as the drift increases. The plate is the first to start the plastic status (0.3% drift), while the u-profile and the bottom plug-in are the last (0.6% drift). The plate achieves maximum yield stress at 1% drift.



a) b)

Figure 10: a) Steel u-Profile stress distribution; b) Plate, upper and bottom plug-ins stress distribution.



a) b)

Figure 11: a) Starting of plastic status; b) Final plastic status.

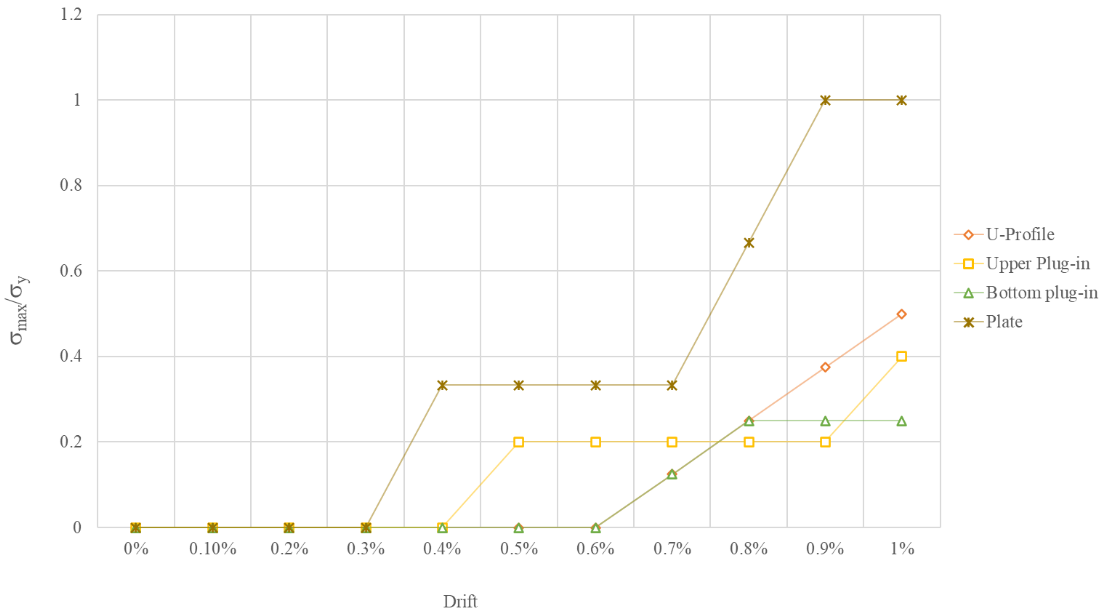


Figure 12: Individual steel element stress status as drift increasing.

4 CONCLUSIONS

This study focused on numerical analysis on a reversible connection for steel modular buildings designed by combining existing connection types from the literature. The modeling has been performed using Midas Fea NX and using the Von Mises material model. This work has focused mainly on the study and proper use of the contact types present within the software. These contact types, moreover, influenced the type of analysis to be performed.

Three types of contact are used for this preliminary study, two of the liner type (Welded contact and Bi-directional sliding contact) and one of the nonlinear type (Rough contact). Welded contact is used for surfaces in contact from the beginning of the analysis, bi-directional sliding contact to consider sliding between the beam and the u-profile, and rough contact for all other surfaces.

By applying a displacement at the upper column, the behavior of the internal connection formed by two plug-ins welded to a plate has been evaluated. The results of the analysis show that the horizontal plate reaches yield stress before the other elements.

The study presented in this paper represents a preliminary investigation on the structural behavior of the connection of the beam-column joint considered. In the future, numerical investigations will be validated with experimental tests, conducted either with static or dynamics lateral loads. The comparisons between numerical and experimental investigations will permit of highlighting how the connection investigating may be improved in order to obtain a better structural performance. Moreover, additional investigations will be conducted in order to take into account different levels of axial load on the preliminary connection considered in this study.

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