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TOWARDS CIRCULAR CONSTRUCTION: CONCEPTS AND EVALUATION OF CONNECT4C MOMENT-RESISTING JOINTS

Summary: The CONNECT4C project promotes circular construction through the development of adaptable and reusable steel joints that combine structural robustness with the requirements of practical engineering design. The project focuses on innovative moment-resisting joint concepts incorporating components such as “long bolts”, “sliders”, and “hyperpacks”, enabling demountable assemblies and providing geometric flexibility for future structural reuse and reconfiguration. This paper presents the fundamental concepts of the proposed joint system and reports the first experimental results from a broader experimental campaign on a two-sided beam-to-beam joint configuration. The tests investigate the behaviour of the connection in the hyperpack–slider interface and the influence of different slider geometries and bolt arrangements on the global response of the joint.

Keywords: circular construction, reusability, adaptability, moment-resisting joints, long bolts

PREMA KRUŽNOJ GRADNJI: KONCEPTI I EVALUACIJA CONNECT4C MOMENTNIH VEZA

Rezime: CONNECT4C projekat promoviše kružnu gradnju kroz razvoj adaptabilinih čeličnih veza za višekratnu upotrebu koje kombinuju konstruktivnu robustnost sa zahtevima inženjerskog projektovanja u praksi. Fokus projekta je na razvoju inovativnih momentnih veza koje uključuju komponente kao što su “dugi zavrtnjevi”, “slajderi” i “hajperpekovi”, a koje omogućuju demontažne sklopove i geometrijsku fleksibilnost za ponovnu gradnju i preuređenje u budućnosti. Ovaj rad objašnjava osnovne koncepte predloženih sistema veza i opisuje prve eksperimentalne rezultate koji pripadaju obimnijoj eksperimentalnoj kampanji na dvostranoj greda-greda vezi. Ispitivanja analiziraju ponašanje veze na spoju hajperpek-slajder, kao i uticaj različitih oblika slajdera i dispozicije zavrtnjeva na globalno ponašanje veze.

Ključne reči: kružna gradnja, ponovna upotreba, adaptabilnost, momentne veze, dugi zavrtnjevi

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1. INTRODUCTION

The construction sector is facing increasing pressure to reduce its environmental impact and transition towards more sustainable and resource-efficient practices. Buildings and infrastructure account for a significant share of global greenhouse gas emissions, energy consumption, and raw material use, making the decarbonization of the built environment a key objective in international sustainability strategies [1]. While considerable efforts have been directed towards reducing operational emissions through improved energy efficiency, increasing attention is now being paid to the embodied environmental impacts associated with the production, transportation, construction, maintenance, and end-of-life treatment of building materials.

Structural steel is widely recognised as a highly recyclable material and is often cited as an example of a resource-efficient construction product [2]. Nevertheless, current design and construction practices largely follow a linear economic model in which steel components are manufactured, assembled into a structure, used during a single service life, and subsequently either disposed of or recycled when the building reaches the end of its operational life. Although recycling enables material recovery and reduces the demand for virgin steel production, it remains an energy-intensive process that requires remanufacturing and results in the loss of a substantial portion of the value embedded in the original structural components.

From a circular economy perspective, direct reuse of structural steel members represents a more desirable strategy than recycling, as it preserves both material and structural value while minimising the need for additional processing. However, widespread implementation of steel reuse requires fundamental changes in design philosophy, particularly with respect to how structures are detailed, assembled, dismantled, and adapted for future applications. Consequently, there is growing interest in developing design approaches and technologies that facilitate the direct reuse of structural steel components and support the transition towards circular construction practices.

2. CONNECT4C CONCEPTS

Building on previous research initiatives in the field of reusable steel structures [3,4], the Connect4C project [5] focuses on developing innovative design solutions that enable the disassembly and subsequent reuse of steel building systems. A fundamental challenge in achieving structural reuse lies in the design of connections. Although steel members may retain significant structural capacity after a building's service life, their reuse is often hindered by connection details not conceived for future disassembly. Conventional connection systems are primarily designed to satisfy structural, economic, and constructability requirements during the initial service life of a structure, with limited consideration given to the possibility of dismantling and reusing the connected components.

To facilitate the direct reuse of structural members, connections must be designed for disassembly. This requires connection systems that can be efficiently separated using standard construction procedures while preserving the integrity of the connected elements. In this context, bolted connections offer significant advantages over welded solutions, as they can generally be dismantled through the removal of fasteners, whereas welded joints often require cutting or other destructive operations that compromise the reuse potential of the members. However, replacing welded details with bolted alternatives alone is insufficient. Connection systems must allow for repeated use over multiple life cycles and maintain the required levels of structural performance, safety, and robustness.

To address these challenges, the Connect4C project investigates reusable connection technologies for moment-resisting joints, pinned joints, and column splices. The overarching objective is to develop connection solutions that combine structural efficiency with demountability, thereby enabling steel structures to be dismantled, reconfigured, and reused in future applications without significant loss of material or structural value.

Beyond demountability, the project also addresses the challenge of adaptability. In practice, structural elements recovered from one building are unlikely to be reused in an identical configuration in subsequent applications. Differences in architectural layouts, structural requirements, spans, and loading conditions often necessitate modifications to the structural arrangement. Since primary steel members such as beams and columns are manufactured with fixed geometrical properties and lengths, connection systems play a crucial role in accommodating these variations and facilitating the integration of reused components into new structural configurations.

To overcome these limitations, the Connect4C project introduces a series of innovative connection components, including elements referred to as the “hyperpack”, “slider”, and “long bolts”. These components are specifically designed to enhance geometric flexibility and facilitate the adaptation of reclaimed structural members to new design requirements while maintaining the necessary levels of structural safety. By combining demountability with adaptability, the proposed solutions aim to maximise the reuse potential of steel structures and support the transition from conventional linear construction practices towards a circular built environment.

Figure 1 illustrates the conceptual framework of the project through the example of a single-storey steel frame. Bolted demountable connections are employed to enable efficient disassembly at the end of the structure’s service life, while additional adaptable components are integrated within the connection zones to accommodate future modifications and facilitate the reuse of structural members in subsequent building lifecycles. This approach seeks to preserve both material and structural value, thereby contributing to more sustainable and circular construction practices.

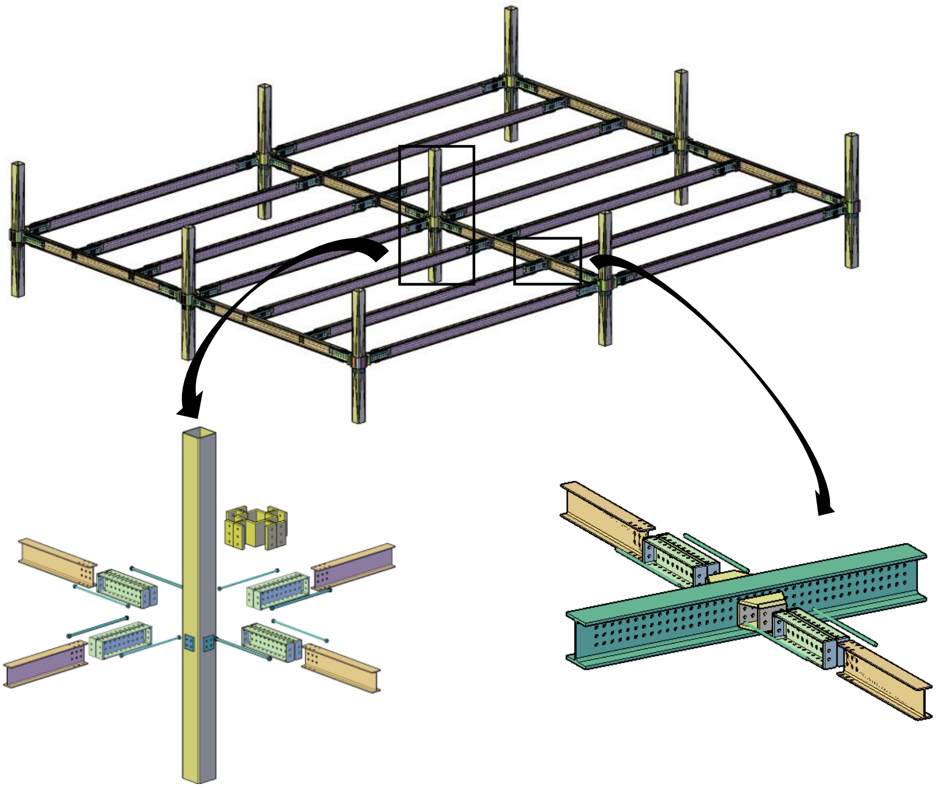


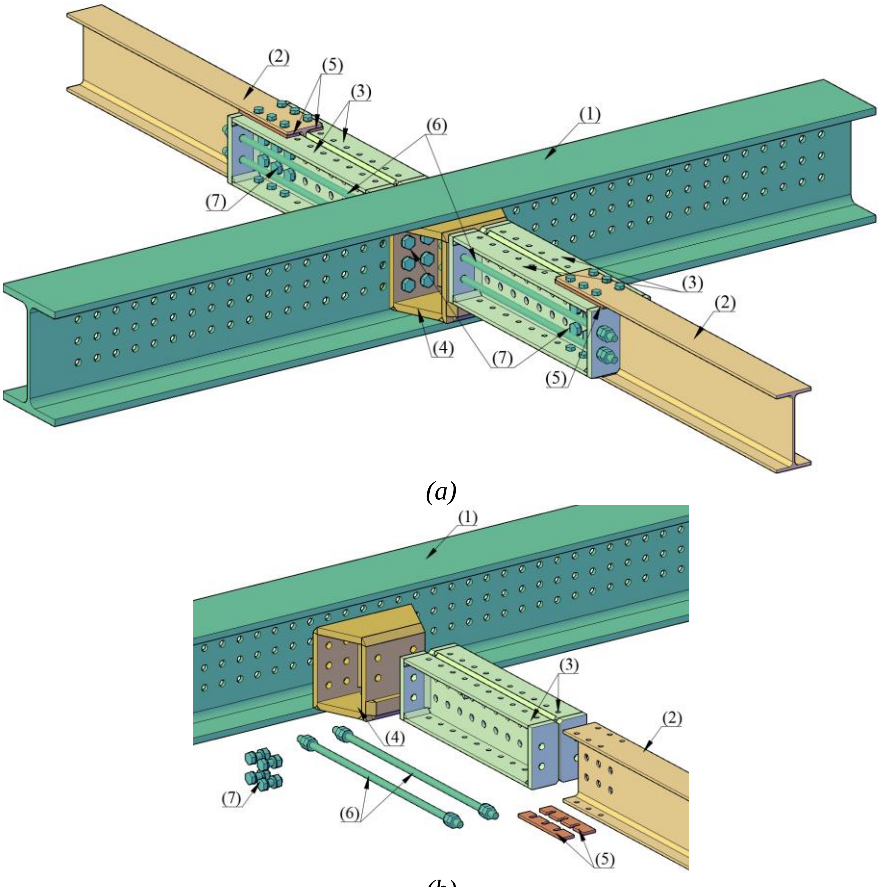
Figure 1: Connect4C conceptual design [6]

3. MOMENT-RESISTING JOINTS

3.1. OVERVIEW

The moment-resisting joints developed within the Connect4C project comprise both beam-to-column and beam-to-beam configurations. This paper focuses on the two-sided beam-to-beam connection [6], which consists of a primary beam connected to two secondary beams framing into it from opposite sides in a perpendicular direction. The assembled and exploded views of the connection are presented in Figure 2.

The proposed connection incorporates several components specifically developed to satisfy the requirements for demountability and adaptability. In addition to the primary and secondary beams (1, 2), the connection includes the novel Connect4C components referred to as the "hyperpack" (3) and "slider" (4), as well as packing plates (5), long bolts (6), and conventional bolts (7).



(a)

(b)

Figure 2: Two-sided beam-to-beam joint: (a) Assembled view; (b) Exploded view [6]

The hyperpack (3) is a prismatic steel component fabricated from five welded plates, as illustrated in Figure 3. It acts as an extension of the connected secondary beam (2). To facilitate geometric adaptability, the hyperpack is perforated along its length with a discrete hole pattern at 75 mm intervals. This arrangement allows the secondary beams to be connected at multiple positions, thereby providing a high degree of horizontal adjustability within the structural system. Owing to the root radius of the connected I-sections, packing plates are introduced to ensure proper fit and load transfer between the connected components, as shown in Figure 3(b). The dimensions of the hyperpack corresponding to an IPE270 section are presented in Figure 3(c). Similar hyperpack variants have been developed for other beam profiles, with each component specifically tailored to the geometry of its associated section. Two hyperpacks are attached to the beam through a conventional bolted splice connection. The connection is established at both the flanges and the web, allowing the hyperpacks to act as a structural extension of the beam.

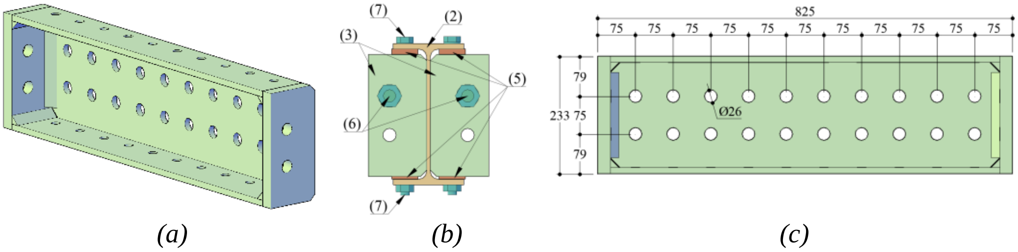


Figure 3: Hyperpack: (a) Isometric view; (b) Packing plates;(c) Dimensions of the hyperpack suitable for IPE270 beam [6]

The slider (4) serves as the intermediate component connecting the hyperpacks (3) and, consequently, the secondary beams (2) to the primary beam (1). The name derives from its ability to move along the web of the primary beam during assembly. When combined with a continuously perforated web of the primary beam (1), the slider can be positioned at different locations along the beam axis, providing adaptability in that direction.

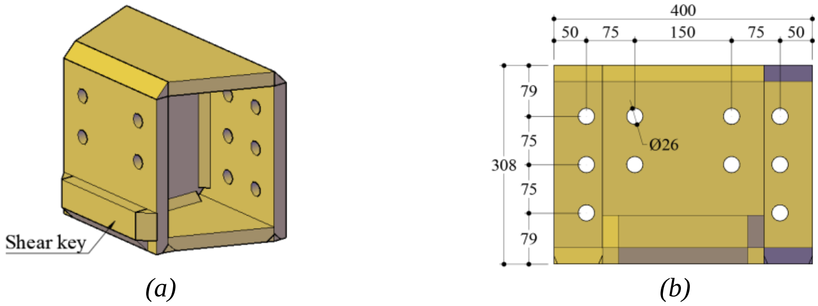


Figure 4: Slider: (a) Isometric view; (b) Dimensions of the slider suitable for IPE270 beam [6]

The transfer of bending moments is achieved through a combination of long bolts (6) and direct contact between elements. Tensile forces are resisted by the long bolts, while compressive forces are transmitted directly through the contact between the opposing surfaces of the slider and hyperpack. These tension and compression zones form a force couple, with the distance between them acting as an internal lever arm that enables the transfer of bending moments. Shear forces are transferred through a dedicated shear key incorporated into the connection and through friction between the surfaces (see Figure 4 (a)).

A distinctive feature of the proposed system is the use of long bolts. In contrast to conventional rigid end-plate arrangements, the long bolts permit controlled opening of the interface between slider and hyperpacks under loading while maintaining the required moment resistance. This behaviour reduces local deformation demands on the end plates, limiting permanent bending and minimising damage to the connection components.

3.2. ADAPTABILITY

The adaptability provided by the proposed moment-resisting connection system is illustrated in Figure 5. A key feature in the provided example is the system's ability to accommodate variations in beam length while maintaining the required structural span. A structural span of 8100 mm can be achieved using a 7450 mm or a 6400 mm secondary beam, as two extremes. The difference in beam length is compensated through the adaptable connection region formed by the hyperpack and slider components, resulting in an effective beam-length tolerance of approximately 1 m.

Alternatively, beams of the same length can be employed to achieve different span dimensions. This is accomplished by adjusting the connection position along the hyperpacks, thereby modifying the effective distance between adjacent structural members.

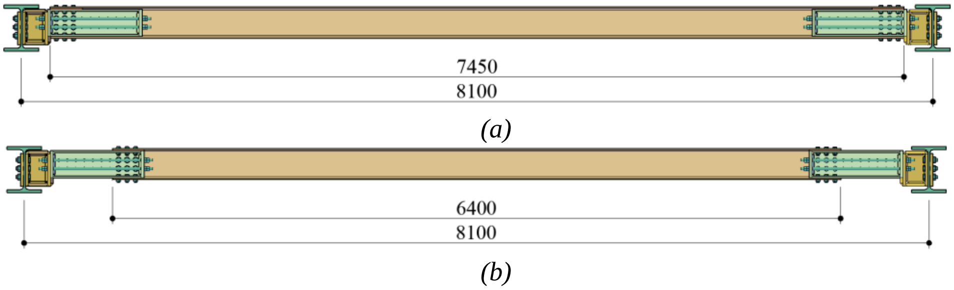


Figure 5: Demonstration of the system´s adaptability

4. CONNECTION VALIDATION

4.1. OVERVIEW

The proposed moment-resisting joint consists of three principal connection interfaces, as illustrated in Figure 6: (1) the connection between the secondary beam and the hyperpacks, (2) the connection between the hyperpacks and the slider, and (3) the connection between the slider and the primary beam. The bolts used in connections 1 and 3 are fully preloaded in accordance with EN 1993-1-8 [7], whereas the bolts in connection 2 are only snug-tightened.

Within the Connect4C project, a comprehensive experimental programme has been planned to validate the structural performance of the proposed connection system. The experimental campaign is structured in stages, with individual connection interfaces being investigated. The first series of tests, presented in this paper, focuses primarily on the hyperpack–slider interface (connection 2), while verifying the integrity and performance of connection 3 under the applied loading conditions.

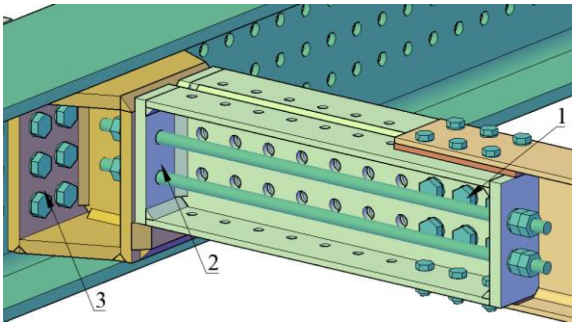


Figure 6: Overview of the moment-resisting joint.

4.2. EXPERIMENTAL PROGRAMME

4.2.1. Objective

As discussed previously, the current experimental programme is primarily aimed at validating the structural behaviour of the connection in the hyperpack–slider interface. A total of four tests were conducted, investigating the influence of two key parameters: the slider configuration and the bolt arrangement.

Two slider variants were considered: a small slider without a shear key (see Figure 7(a)) and a big slider incorporating a dedicated shear key (see Figure 7(b)). In addition, two bolt configurations were examined. The first configuration consisted of one row of long bolts and one row of conventional bolts (LB + CB), as illustrated in Figure 7(c), while the second configuration employed two rows of long bolts (2LB), as shown in Figure 7(d). The experimental matrix is summarised in Table 1.

Table 1: List of tests

Test	Slider	Bolt configuration
T1a	Small	LB + CB
T1b	Small	2LB
T2a	Big	LB + CB
T2b	Big	2LB

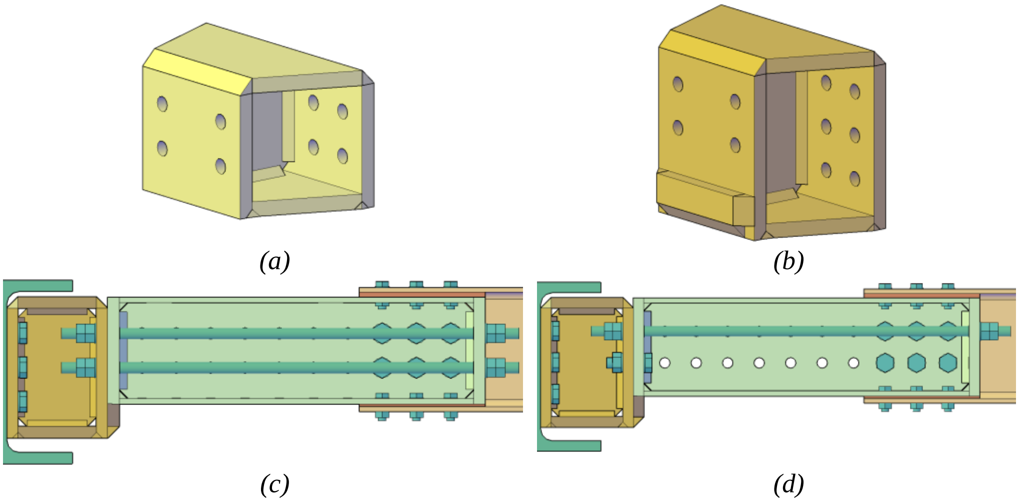


Figure 7: Testing parameters

4.2.2. Testing layout

The experimental setup is illustrated in Figure 8. The primary beam (201) was positioned centrally within the reaction frame (101) and subjected to vertical loading through a 3 MN hydraulic actuator mounted at the top of the frame. In the actual structural configuration, loads would be transferred from the secondary beams (202) to the primary beam through the connection assembly. However, to simplify load application and instrumentation, the test configuration was inverted, with the load applied directly to the primary beam. This arrangement reproduces the force-transfer mechanism within the connection while providing convenient access for testing and measurements.

The tested assembly comprised all principal connection components, including the primary beam (201), secondary beams (202), sliders (203), hyperpacks (204), and packing plates (205, 206). A guiding system (105) was incorporated to ensure controlled vertical displacement of the primary beam during loading. The secondary beams were supported by pinned supports (104). To prevent unintended out-of-plane displacements and ensure the stability of the setup, a lateral restraint system (106) was installed. The entire setup was mounted on the bottom beam (102), with the support structures located beneath the load cells (103).

The applied force was measured using load cell LC1, positioned directly below the hydraulic actuator. In addition, load cells LC2 and LC3 were installed at the supports to monitor the reaction forces. This instrumentation scheme enabled accurate measurement of both the applied load and its distribution throughout the test specimen.

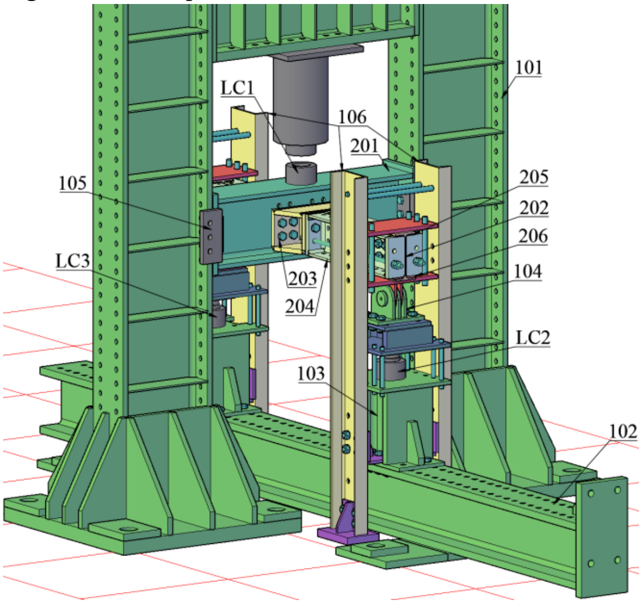


Figure 8: Testing layout [6]

4.2.3. Preliminary results

In all four tests, the anticipated failure mode was observed, namely fracture of the long and conventional bolts located at the hyperpack–slider interface. No slip was detected in the slider-to-main-beam connection throughout the tests, confirming that the response of the assembly was governed by the behaviour of the hyperpack–slider interface. The locations of the reference planes used for the evaluation are defined in Figure 9, while the corresponding bending moment (M_i) and shear force (V) distributions are presented in Figure 10(a) and Figure 10(b), respectively. A summary of the experimental results, including relative rotation in planes C1 and C2 ($\Delta\phi_{C,i}$, where i=1,2), is provided in Table 2.

The theoretical bending moment resistance in planes C1 and C2, denoted as ($M_{C,theo.}$), was determined by assuming that the behaviour is governed by the bolts in the hyperpack–slider interface. The theoretical resistance was therefore calculated as the product of the bolt tensile resistance and the corresponding internal lever arm.

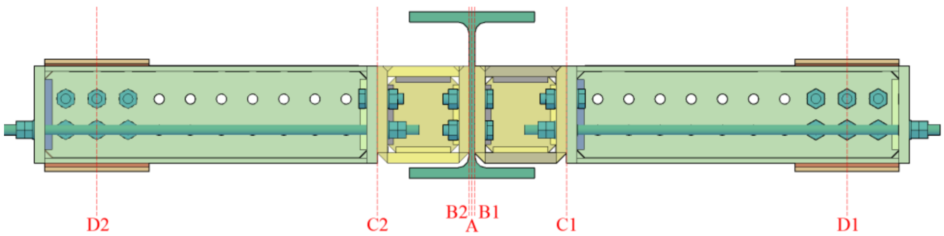


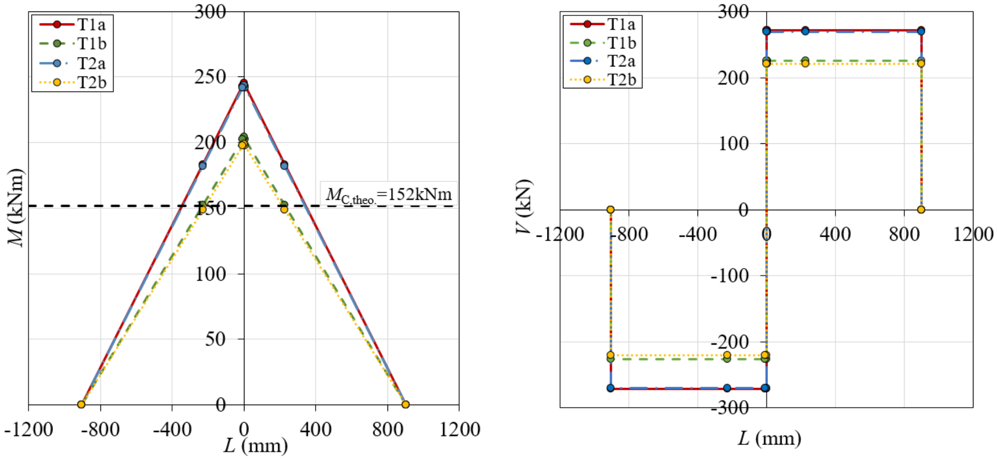
Figure 9: Defined vertical planes

The experimental results indicate that connections incorporating the LB + CB bolt configuration achieved approximately 20% higher bending moments in the central plane (A) than the corresponding specimens with the 2LB configuration, regardless of the slider type.

The connection exhibited substantial rotational capacity in all tests. Mean relative rotations, in all tests, between the hyperpack and slider measured in planes C1 and C2 reached values of 55.0 mrad and 51.9 mrad, respectively. This large deformation capacity can be attributed to the flexibility provided by the long bolts, which allow controlled opening of the interface while maintaining force transfer. Furthermore, specimens equipped with two rows of long bolts (2LB) exhibited approximately 35% greater rotational capacity than those with the LB + CB configuration.

Visual inspection following the tests confirmed that the damage was primarily concentrated in the long bolts. The hyperpack behaved largely as a rigid body, with no observable hole bearing and only minor deformation of the end plate. The slider remained elastic throughout all tests.

In the specimens with the 2LB configuration, load transfer was initially concentrated in the first row of long bolts, while the second row became progressively engaged as deformation increased. In contrast, for the LB + CB configuration, the conventional bolts contributed to bending moment transfer from the early stages of loading, resulting in a different force distribution within the connection.



(a) *(b)*

Figure 10: Internal forces: (a) Bending moment; (b) Shear force

Table 2: Results summary

Test	M_{D1} (M_{D2}) [kNm]	M_{C1} (M_{C2}) [kNm]	$\Delta\phi_{C,1}$ [mrad]	$\Delta\phi_{C2}$ [mrad]	M_{B1} (M_{B2}) [kNm]	M_A [kNm]	V [kN]
T1a	0.0	183.3	35.4	40.1	243.2	245.1	271.6
T1b	0.0	152.6	61.8	65.0	202.5	204.1	226.1
T2a	0.0	182.1	46.2	42.2	241.6	243.5	269.7
T2b	0.0	148.9	76.8	60.3	197.6	199.1	220.6
Mean	0.0	166.7	55.0	51.9	221.2	223.0	247.0
CoV [%]	-	11.1	32.9	24.2	11.1	11.1	11.1

5. CONCLUSIONS

This paper presents the concept of moment-resisting joints developed within the framework of the Connect4C project. The primary objective of the proposed connection system is to support circular construction principles by enabling the reuse and adaptability of steel structures. To achieve this, the connection incorporates additional components that facilitate non-destructive disassembly and allow structural members to accommodate potential layout modifications in future life cycles.

A comprehensive experimental programme has been planned to validate the proposed connection system. This paper presents the preliminary results from the first testing campaign, focusing on the two-sided beam-to-beam configuration. A total of four tests were conducted, investigating the influence of the slider type and the bolt configuration within the hyperpack–slider interface.

The presented work forms part of an ongoing research programme that also includes detailed numerical modelling and parametric studies. The ultimate objective is to develop a design methodology based on the Eurocode component method, enabling the practical design and future implementation of these adaptable and reusable moment-resisting joints in engineering practice.

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