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Full paper

WAAM Integrated Plug-and-Play Beam-to-Column Connection

Grigor Ayvazyan[1], Trayana Tankova[1], Milan Veljkovic[1]

Correspondence

Dr. Trayana Tankova
Delft University of Technology
Department of Engineering
Structures
Stevinweg I
2628CN Delft
Email: t.tankova@tudelft.nl

[1] Delft University of Technology,
Delft, the Netherlands

Abstract

This paper presents the development and evaluation of a novel plug-and-play beam-to-column connection for steel structures, designed to facilitate rapid on-site assembly, enable structural reuse, and reduce material usage. The connection concept was refined through an iterative design process focused on minimizing material consumption while maintaining structural performance. Finite element analysis was employed at each iteration to evaluate the joint's stiffness and moment resistance, with validation based on experimental data. The final plug-and-play connection was compared to a conventional single extended end-plate bolted connection using equivalent beam and column sections. Results show that the plug-and-play joint achieves a 26.1% reduction in material use while offering higher stiffness and moment capacity. Yielding behavior differs between the two connections, with the plug-and-play joint developing plasticity at higher loads, thereby extending potential for reuse. Classified as semi-rigid and partial strength, the connection supports moment-resisting frame applications. The proposed design demonstrates a viable and efficient alternative to traditional bolted joints, with opportunities for further optimization and expanded applications.

Keywords

Plug-and-play connection, Steel, WAAM, Optimization

1 Introduction

Growing awareness of the environmental impact of human activity has intensified the global focus on sustainability. The urgent need to transition energy sources, reduce greenhouse gas emissions, recycle and reuse construction materials, and minimize overall climate impact has become a shared societal priority [1]. As a major contributor to carbon emissions - accounting for approximately 5% of CO_2 emissions in the EU and 7% globally - the steel industry must adopt new technologies and re-evaluate traditional design philosophies to align with climate targets and reduce its environmental footprint [2].

Efforts to reduce global steel production focus on improving manufacturing processes, optimizing structural design, extending the service life of structures, and promoting the direct reuse of steel components without remelting [3]. A key factor in achieving these goals lies in the design of steel structures, particularly the detailing of beam-to-column joints, which are critical for effective load transfer and structural integrity. These joints must not only satisfy structural requirements but also support efficient use of materials and minimize on-site labor and time during installation.

Traditional beam-to-column joints are typically categorized as either bolted or welded connections [6]. Both connection types are labour-intensive—bolted joints require precise assembly, while welded joints demand skilled labour and careful execution. Especially for on-site welding, the processes involved are complex, time-consuming, and costly [4].

To support the broader strategy of reducing steel production, there is a pressing need to rethink the design, fabrication, and assembly of structural joints. One promising solution is the adoption of plug-and-play connections - prefabricated joints that are designed for simple, rapid installation on-site. These connections can facilitate the reuse of structural elements and promote circularity and sustainability in steel construction.

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This paper investigates the application of the plug-and-play concept in conventional beam-to-column moment-resisting joints. A new design is proposed and further optimized considering the integration of innovative technologies such as Wire Arc Additive Manufacturing (WAAM) to optimize joint design. The proposed plug-and-play joint is compared with a standard end-plate connection in terms of performance, efficiency, and sustainability.

2 Innovative connections

Plug-and-play connections in structural engineering refer to prefabricated joints designed for off-site manufacturing and rapid, straightforward on-site assembly, typically requiring minimal or no additional fastening. These connections aim to streamline the construction process, reduce on-site labour demands, minimize erection errors, and enable immediate structural use upon installation [5]. A significant advantage of this approach is its potential to enhance the reusability of structural components, which is a key strategy for reducing the environmental impact of steel construction. Reuse of steel elements not only lowers material consumption but also encourages new design methodologies that support circular construction principles. However, the practical implementation of reusable systems is often hindered by challenges such as quality assurance, traceability, certification of reclaimed components, and limited supply chain integration [6]. Therefore, for plug-and-play systems to be truly effective, the entire structure must be designed with reuse in mind, not just the connections. This includes avoiding welding, minimizing plastic deformation during service, and using standardized, easily disassemblable components. Prominent examples of plug-and-play solutions include the INNO3DJOINTS and ConXtech systems. The INNO3DJOINTS project developed a connection for cold-formed or tubular trusses to tubular columns (Figure 1), using a T-plug and socket mechanism that allows quick installation with only minimal bolting. This system demonstrated successful full-scale reuse, having been disassembled and re-erected in a different location, and its components are designed for mass production, enhancing cost-competitiveness [7].

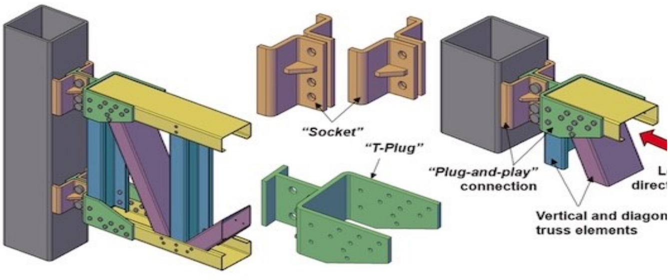


Figure 1 INNO3DJOINTS plug & play connection [7].

The ConXtech system (Figure 2), in contrast, includes a range of plug-and-play beam-to-column connections (e.g., ConXL and ConXR series) that employ a collar-based plug-and-socket design. These joints allow for rapid assembly without on-site welding and are pre-qualified for seismic performance, making them attractive for high-performance structures [8]-[11]. However, their design requires full collar assemblies on all column faces, even when fewer beams are used, leading to material inefficiencies. Furthermore, their applicability is limited to specific SHS column sizes and excludes CHS columns, restricting flexibility in design. Despite these limitations, ConXtech has successfully implemented these joints in various commercial projects, demonstrating their real-world viability.

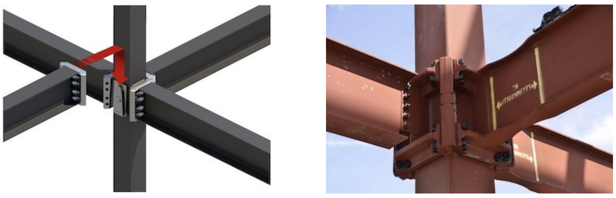


Figure 2 ConXR200 and ConXL400

Wire Arc Additive Manufacturing (WAAM) has emerged as a promising fabrication method for structural steel components, offering greater geometric flexibility than conventional rolling or machining processes. Its suitability for producing complex, non-standard geometries makes it particularly attractive for structural joints, especially when combined with computational design techniques such as topology optimization (TO). One notable example is ARUP's development of a topologically optimized steel node for a lighting structure, which achieved a 25% reduction in the self-weight of the node and contributed to a 40% overall reduction in structural mass [12]. This project highlighted the potential of combining WAAM with TO to produce material-efficient, performance-driven structural components.

Other research initiatives, such as the Takenaka connector [13] and several university-led developments [14], have further demonstrated how WAAM can be used to fabricate bespoke structural joints shaped through form-finding or performance-based design processes. These examples illustrate that WAAM is capable not only of realizing TO-derived geometries but also of addressing the growing need for modularity, customization, and sustainability in construction.

3 Plug-and-Play Design

The design of the plug-and-play connection is based on the practical limitations and advantages which have been observed in the connections presented in the literature review and the absence of a plug-and-play semi-rigid and partial strength beam-column joint in the field. A semi-rigid and partial strength joint allows to design a structure as a moment-resisting frame [7] and can provide several benefits such as sufficient lateral bracing for usual wind loads in low-rise buildings to prevent the use of bracing elements and more distribution of the bending moments in the structure [15].

Considering that the plug-and-play joint was intended to be semi-rigid and partial strength, the monotonic load application and that bolted connection can be reused, a single extended endplate bolted connection was taken as the basis for the plug-and-play design. The single extended endplate bolted connection was designed according to Eurocode 3, Part 1-8 to be semi-rigid and partial strength. This bolted connection functioned as the reference case to which the plug-and-play connection is compared to for design purpose.

3.1 Conceptual design

The conceptual design of the plug-and-play connection assumes that installation should require only one worker per side of the beam-end, similar to the SidePlate connection [16], ensuring simplicity and minimal labour. The beam should be installed through a single downward movement, as demonstrated by systems like INNO3DJOINTS, ConXtech, and SidePlate, avoiding complex multi-step procedures. The connection must allow beams to be connected to any side of the column - either individually or simultaneously - without necessitating components on all faces, addressing the limitation of ConXtech's requirement for a full collar flange assembly. To support broader applicability, the design should be compatible with a variety of column and beam configurations, unlike ConXtech which is restricted to specific SHS sizes. Furthermore, it should be adaptable to different column types, including SHS, CHS, RHS, and open sections, as achieved in the INNO3DJOINTS system. Lastly, while innovative manufacturing methods like additive manufacturing may be integrated, their use should be minimized due to high costs, energy demands, and practical constraints, as highlighted by experiences with ARUP's structural nodes [12] and the N-type and Glass swing nodes [18].

The proposed plug-and-play connection consists of three main components: two pins, a grip-plate, and a compression foot. The grip-plate functions similarly to a traditional endplate and is subdivided into three parts: the back-plate, middle-plate, and front-plate. The back-plate shares the same dimensions as a standard endplate. The middle- and front-plates are extended vertically to accommodate the full height of the pins. Slots are integrated into the grip-plate to receive the pins and facilitate the transfer of tensile forces from the beam to the pins. The pins are designed to replicate the mechanical function of the upper three rows of bolts in a conventional bolted connection, which primarily resist tensile forces. They occupy the same width-wise positions on the column flange and match the vertical placement of the original upper bolt row. Each pin comprises a shank and a face; the shank is narrower than the face and acts as a plug, fitting into the corresponding slots in the grip-plate. The third component, the compression foot, is placed directly onto the column flange without any mechanical fastening. It serves to transfer compressive forces from the beam into the column. The conceptual design of this plug-and-play connection is depicted in Figure 3.

The connection is assembled through two simple beam movements. First, the beam is positioned horizontally to align the pins with the corresponding slots in the grip-plate. Then, it is lowered vertically, allowing the pins to slide into the slots and fully engage with the grip-plate, thereby completing the connection. This conceptual plug-and-play design meets the defined performance and design requirements, offering a straightforward and efficient assembly process suitable for rapid on-site installation.

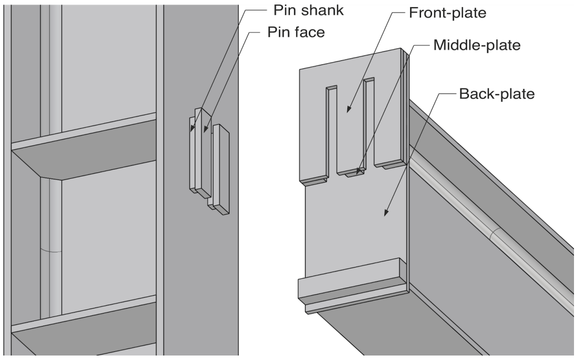


Figure 3 Conceptual design plug-and-play connection

4 Plug-and-Play Optimization

4.1 Methodology

The development of the plug-and-play connection was achieved through a series of iterative modifications aimed at minimizing material usage while maintaining structural performance and adhering to the defined design requirements. These modifications were applied to the pins, grip-plate, and compression foot. The following section outlines the iterative process, describes each modification, and evaluates its impact on the joint's behaviour. The final design emerged as a result of these successive refinements.

4.2 Numerical model

The finite element (FE) model was developed and validated against an experimental test conducted in 2009 at the University of Coimbra [19]. This experiment served as the benchmark for assessing the accuracy of the numerical model. The model utilizes solid C3D8R elements with enhanced hourglass control to mitigate numerical instabilities. To ensure adequate through-thickness representation, three element layers were used across the thicknesses of all structural components.

Contact interactions in the model are governed by the general contact algorithm. A friction coefficient of 0.3 is applied to simulate realistic surface interaction, and separation after contact is permitted to capture potential gapping effects during loading. A mesh sensitivity study was performed to determine the optimal element size for each component, balancing computational efficiency and result accuracy.

Material properties for the columns and beams were derived from the average values of tensile-tested steel coupons taken from various parts of the experimental setup, including the web and flanges of the beam and column, the end-plate, and stiffeners [19]. Similarly, bolt properties were based on the average tensile behavior of tested bolts from the same experiment. For the WAAM components, mechanical properties were obtained from tensile tests on coupons extracted from a CMT-WAAM manufactured wall, tested in different orientations relative to the printing direction [17].

To evaluate joint rotation, two nodes—DT11 and DT12—were defined at the top and bottom flanges of the beam-end, centrally aligned with the column face (see Figure 4). The horizontal displacement of these nodes was extracted to calculate the rotation, θ, assuming a straight line between them. This line forms an angle with the vertical axis, capturing both the rigid-body rotation of the beam-end and the elastic deformation of the adjacent column.

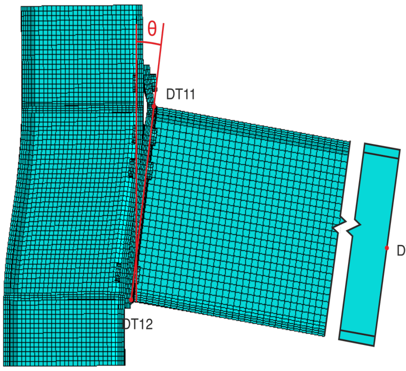


Figure 4 Global rotation

The moment-rotation behavior was characterized using the method illustrated in Figure 5. Initial stiffness, $S_{j,ini}$, was determined by fitting a straight line through the origin and the linear segment of the moment-rotation curve. The elastic moment resistance, M_{el}, was identified at the point where the curve deviated from this linear behavior. The plastic moment resistance was defined as the intersection point of the initial stiffness line and the limit stiffness line—a straight line approximating the post-yield stiffness of the joint [20].

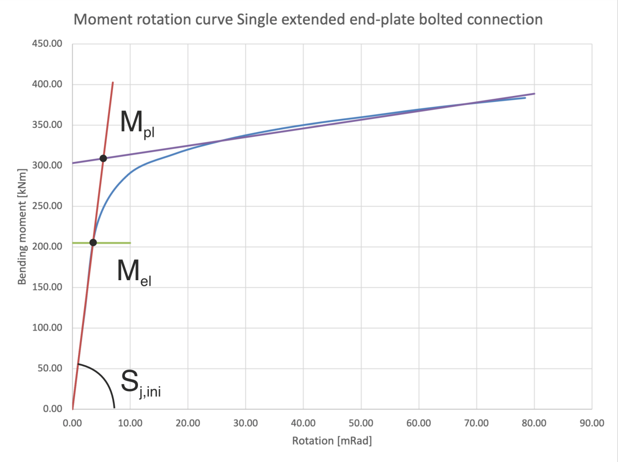


Figure 5 Moment-rotation curve single extended end-plate bolted connection

4.3 Iterative analysis

The iterative process began with the analysis of the conceptual plug-and-play joint model. For each iteration, a numerical simulation was conducted, and the resulting moment-rotation curve was generated. Joint characteristics were then extracted from the curve which was obtained according to the methodology described in the previous section. As the conceptual model served as the baseline, no comparison was made in the first iteration. In subsequent iterations, a single parameter or component geometry was altered in the model, followed by simulation and analysis. The new joint characteristics were compared with those of the previous iteration to evaluate the effect of the modification. This feedback loop concluded each iteration and informed the next step in the process. The final iteration, which no longer required further modification, defined the final design of the plug-and-play connection. This iterative design workflow is schematically illustrated in Figure 6.

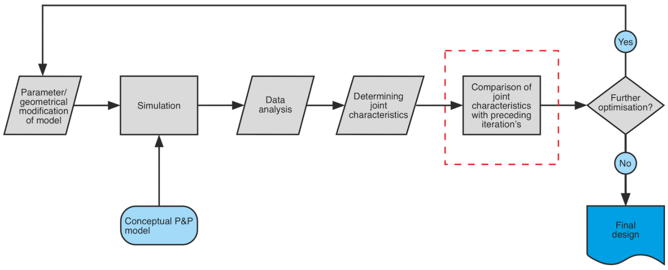


Figure 6 Conceptual design plug-and-play connection

The results from the iterative analyses at each step are presented in Table 1.

Table 1 Iterative analyses

Iteration	Description	$S_{j,ini}$ [kNm/rad]	M_{el} [kNm]	M_{pl} [kNm]
	Conceptual design	**72044**	**265**	**321**
1	Pins	-0.1%	0.0%	-0.5%
2	WAAM pins	0.0%	-1.9%	-1.0%
3	Short pins (-35 mm)	-1.4%	0.0%	+0.3%
4	Round pins	+0.2%	-1.9%	-0.1%
5	Short pins (-18 mm)	-0.4%	0.0%	+1.2%
6	Pins 2 mm tolerance	-1.4%	0.0%	-2.2%
7	Compr.foot - 15 mm	+4.8%	0.0%	+3.2%
8	Shorter grip-plate	-2.3%	+2.0%	-0.8%
9	Removal back-plate	-0.4%	0.0%	-0.7%
10	Smaller compr. foot	-2.1%	-1.9%	+0.1%
11	Higher compr. foot (on top)	+2.7%	0.0%	+1.3%
12	Compr. foot 40 mm lower	-0.1%	0.0%	0.0%
13	Adjust. middle column part with finer mesh	-0.3%	0.0%	+0.5%
All	**Total change from conceptual to final design**	**-1.1%**	**-3.8%**	**+1.2%**
		71478	**255**	**325**

The configuration of the final plug-and-play connection is presented in Figure 7, where the pins are produced using WAAM and the grip plate conventional machining process.

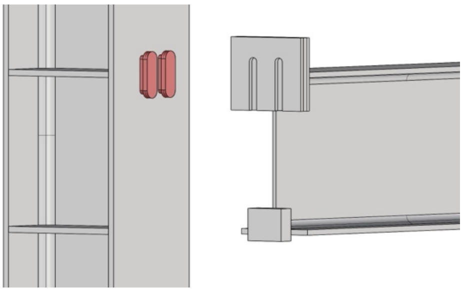
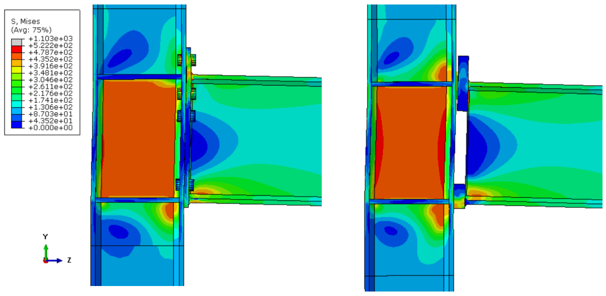


Figure 7 Conceptual design plug-and-play connection

4.4 Comparative analysis

The final design of the plug-and-play connection was compared to a conventional single extended endplate bolted connection, which served as the case study. In both cases, the column was a HEA300 section and the beam an IPE400 section. The bolted connection featured a 15 mm thick endplate measuring 190 × 500 mm², secured with eight M24 10.9 full-threaded bolts. The comparison focused on two primary aspects: structural performance and material usage.

Structural behavior was assessed based on initial stiffness, elastic moment resistance, and plastic moment resistance of the joints. Figure 8 presents the global response of both joints at their respective plastic moment resistance levels. In the bolted connection, initial yielding is observed in the endplate, primarily due to local bending. This behavior results in relatively low stress levels in the column web, particularly above the upper transverse stiffener, as illustrated in Figure 8a.



a) endplate connection

b) plug and play

Figure 8 Comparison between endplate and plug-and-play connections

Conversely, in the plug-and-play joint, initial yielding occurs in the tension-loaded pins and in the column web panel. As shown in Figure 8b, higher stress concentrations are evident in the column web panel and in the region above the upper transverse stiffener, indicating a different load transfer mechanism compared to the bolted connection.

These differences in stress distribution arise from the distinct failure mechanisms in the tension zones of the two joints: bending in the endplate for the bolted joint, and tensile loading of the pins for the plug-and-play joint. However, in the compressive zones of the joints, the structural behavior is largely comparable, with similar stress patterns observed in both cases.

Table 2 Comparison between bolted and final plug-and-play connection results

	$S_{j,ini}$ [kNm/rad]	$M_{el,Rd}$ [kNm]	$M_{pl,Rd}$ [kNm]
Bolted connection	57494	205	309
Plug-and-play connection	71478	250	325
Difference	+24.3%	+22.0%	+5.2%

The material usage of the final plug-and-play connection is compared to the single extended endplate bolted connection. In the comparison, the following parts are related to each other: endplate and grip-plate, bolts in tension and pins, bolts in compression and compression foot. The total material usage of the plug-and-play connection is much lower than for the bolted variant, 26.1% less. The difference is mainly due to the grip-plate using less steel than the endplate.

It is noted the plug-and-play connection uses less material (-60.4%) in the tension zone and more material (+133.9%) in the compressive zone, than the bolted connection. However, the pins and compression foot combined use less material than all the bolts in the bolted connection (-11.8%).

5 Conclusion

his study presented the development and evaluation of a novel plug-and-play beam-to-column connection for steel structures, designed to support rapid assembly, reusability, and material efficiency. The final design emerged through a structured iterative process aimed at minimizing material use while preserving key structural performance parameters. Each iteration involved targeted modifications to individual components—pins, grip-plate, and compression foot—followed by numerical analysis and comparison with previous iterations. The result was a refined design that meets the predefined design requirements and outperforms the conventional single extended endplate bolted connection in several aspects.

The final plug-and-play connection demonstrated a 26.1% reduction in overall material usage compared to the bolted connection. This efficiency is largely attributed to the more optimized geometry of the grip-plate and the integrated design of the pins and compression foot. While the plug-and-play joint uses more material in the compressive zone, it significantly reduces material in the tensile zone, and its total fastener-related material is also lower. Importantly, the joint achieves higher stiffness and moment resistance than the reference bolted joint, indicating more effective use of less material.

Finally, the design of the connection is well-suited for production using Wire Arc Additive Manufacturing

(WAAM), particularly for the pins and grip-plate. WAAM allows for efficient fabrication of geometrically complex or customized components with reduced material waste, making it a promising method for producing the plug-and-play joint at scale. However, due to cost and energy considerations, the use of WAAM should be applied selectively and optimized for critical components.

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