Laser-cut I-beam-to-CHS column moment-resisting steel joints

Peer-reviewed author version

DAS, Rajarshi; GOUVEIA HENRIQUES, Jose & DEGEE, Herve (2020) Laser-cut I-beam-to-CHS column moment-resisting steel joints. In: Steel construction (Berlin. Print), 13 (2) , p. 92 -97.

DOI: 10.1002/stco.202000006

Handle: http://hdl.handle.net/1942/31908

Laser-cut I-beam-to-CHS column moment-resisting steel joints

Rajarshi Das[a], José Henriques[a,*] and Hervé Degée[a]

[a] CERG, IIW, Hasselt University

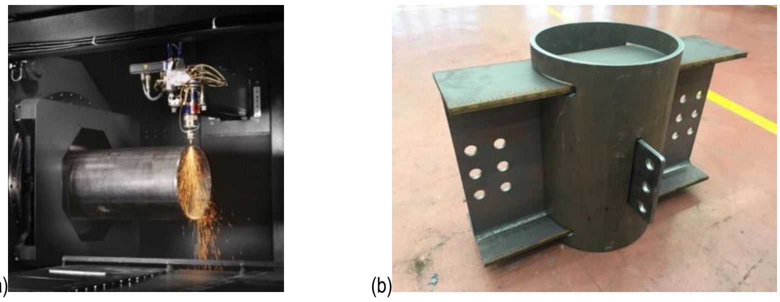
Although open-to-circular hollow section (CHS) connections are highly encouraged in the current structural steelwork industry thanks to the extensive range of advantages provided by the CHS columns, a complicated and expensive fabrication procedure has limited their application in practice. The additional gusset plates or stiffeners needed to strengthen a conventional open-to-CHS connection lead to excessive welding quantities and localized CHS distortion, thus causing an economic as well as structural disadvantage. However, if designed efficiently, the CHS connections can offer an extensive range of solutions for modern multi-storey structures. To that end, different types of nominally pinned and moment-resisting "passing-through" open-to-CHS connections have been developed using laser cutting technology (LCT) and proposed by the European research project LASTEICON. This current article concentrates on the LASTEICON two-way moment-resisting connections. The non-linear behaviour of the connections is discussed by way of an appropriate understanding of the force transfer mechanism. Furthermore, these innovative connections are compared with directly welded conventional open-to-CHS connections in order to highlight the advantages offered by the "passing-through" approach.

Keywords: open-to-CHS-column connection; tubular structures; CHS joints; hollow section joints; through-plate connections; through-beam connections; passing-through joints

1 Introduction

Steel circular hollow sections (CHS) represent competitive solutions for columns when compared with open steel sections. The higher unit cost of the CHS is compensated for by their structural efficiency in terms of excellent resistance to high compression, tension and bending in all directions, thanks to their inherent shape and geometry [1]. Furthermore, tubular sections offer the chance of lightweight structures and require a lower volume of fire protection material compared with their equivalent H-sections [2]. However, as open sections remain the universally preferred choice for beams, the use of CHS columns requires open-to-CHS connections. To that end, open sections are generally connected to CHS columns by a direct welding technique or by using additional diaphragm plates around the CHS column. In the last few decades, CIDECT has provided significant knowledge based on current industrial practice in order to design such open-to-hollow section connections [3]. These conventional connections require a significant amount of welding plus stiffeners and gussets, which makes the fabrication and production processes complicated and expensive. Additionally, comprehensive research studies [4] in the past have shown that these conventional open-to-CHS connections are often prone to severe local distortion at the CHS column wall and premature flange fractures due to the direct welding technique. As a result, even though several design guides and research studies had been published regarding these CHS columns and their connections, engineers have refrained from using them in modern structures.

Therefore, several research projects have used different innovative approaches in order to improve the I-beam-to-CHS joints. Among various alternatives, the “passing-through’ approach [5] provided promising results and hinted at an efficient solution. Nevertheless, detailed results had not been recognized, probably because of the practical difficulties caused by the traditional cutting process – manual fabrication as well as tolerance control. An alternative to such traditional cutting techniques is laser cutting technology (LCT), a thermal cutting process where the laser beam energy (Fig. 1a) is converted into heat energy to melt the metal on the working surface with the help of a pressurized gas (e.g. oxygen). Cutting takes place when the laser beam hits the specimen. Compared with traditional cutting techniques, LCT offers substantial advantages such as: significant reduction in welding quantities, swift fabrication process, tolerance control, better precision and minimization of human error, with better workplace safety through computer-programmed automation. Thanks to this new laser cutting technology, several joint configurations were therefore developed and investigated in this research by way of a “LASTEICON” solution, initially proposed by a European project [6]. This involves an I-beam or steel plates passing through LCT slots made in the CHS column and the primary beams (called “main” I-beams) being connected to both ends of the member(s) passing through (called “through” members). The applied moment is effectively transferred by the through-I-beam to the CHS column, and the CHS contributes significantly to resisting it through its resistance to transverse tensile/compressive forces. Further details regarding the complete fabrication process applied to the LASTEICON joints, with quantification of the time and resources spent during the process, was discussed in a first study [7]. Furthermore, a detailed description of the laser cutting procedure was also provided to show its potential in the steel construction sector [7]. An example of the laser cutting process is shown in Fig. 1a, while Fig. 1b shows a four-way LASTEICON joint configuration.



(a) (b)

Fig. 1 a) Laser cutting operation; b) a four-way LASTEICON connection configuration with I-beams and plates passing through the CHS column via LCT slots [8]

The LASTEICON connections were developed for both two-way and four-way joints considering different “through” members, e.g. I-beam or steel plate(s), and different combinations of nominally pinned/moment-resisting connection properties. Seven different I-beam-to-CHS connection configurations were developed and investigated by way of detailed numerical simulations and experimental investigations [6]. As a detailed perspective for some of these connections is still under development and requires further documentation, this present investigation focuses on the LASTEICON two-way moment-resisting configurations, namely C3 (Fig. 2a) and C4 (Fig. 2b). Case studies are discussed to explain the force transfer mechanism of both configurations under different types of loading scenario. The LASTEICON connections are further compared with conventional open-to-CHS connections to showcase the advantages offered by the “passing-through” approach.

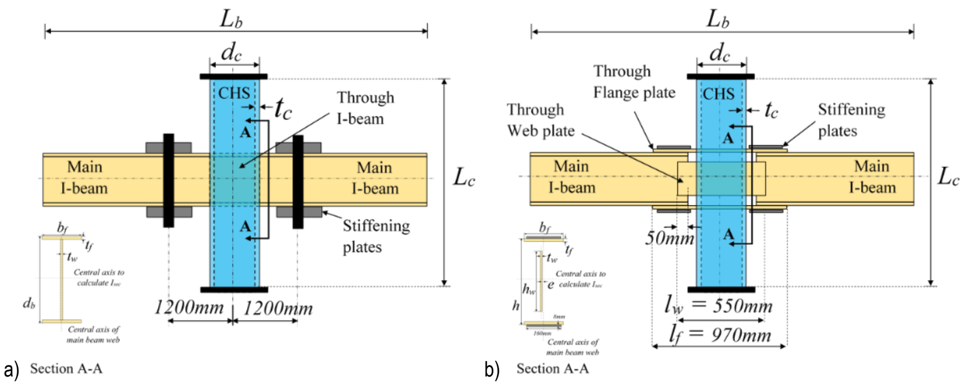


Fig. 2 Relevant parametric dimensions for a) LASTEICON C3 configuration and b) LASTEICON C4 configuration

2 LASTEICON two-way moment-resisting connections

2.1 Design methodology

Two different load cases were considered to acquire a detailed understanding of the moment connection behaviour for both LASTEICON configurations. LC1 defines a monotonic gravitational loading with two unidirectional vertical loads, each acting at the end points of the main beam (Fig. 3a), whereas LC2 denotes a monotonic opposite bending load, where the two loads were applied in opposing directions (Fig. 3b). Therefore, two different design procedures were developed for each configuration, C3 and C4, for two different loading scenarios based on comprehensive parametric analyses. Detailed design guidelines regarding both configurations were documented in a previous research study [8] and are not discussed here. The force transfer mechanisms were suitably identified and are discussed in section 2.3.

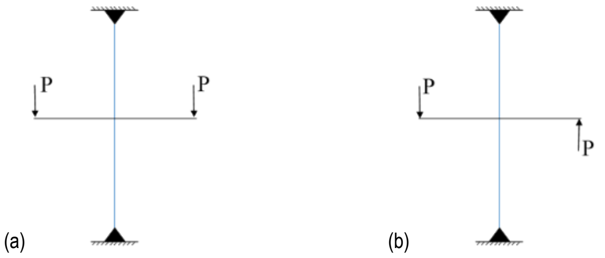


Fig. 3 Load cases: a) LC1 – monotonic gravitational loading, b) LC2 – monotonic opposite bending loading

2.2 Modelling approach and experimental calibration

The proposed connections were analysed in non-linear static analyses using the FE commercial software DIANA 10.2 [9]. The laser-cut slots in the CHS column were taken into account to position the through-members. Nevertheless, to avoid any secondary connection failure and focus on the "passing-through" zone, the slots in these numerical models were made with zero tolerance, thus connecting the CHS column with the through-members assuming a perfectly welded connection. A detailed experimental campaign was carried out by INSA [10] to validate the numerical models for both load cases. Solid circular plates were connected to each extremity of the CHS column which were finally pinned by rollers following the boundary conditions, and bracing members were included to limit the lateral torsional buckling of the beam. These elements were also considered in the numerical models (see Fig. 2) to obtain a reliable replica of the experimental specimens and thus provide an appropriate validation. Loads were applied at the furthest extremity of the main beams. Material properties for the numerical models were adopted according to the stress-strain relationship obtained from the experimental coupon tests. The force-displacement curves and the failure modes were compared between the experimental and numerical results and very good agreement was obtained in terms of initial stiffness, ultimate resistance and failure mode of the connections. The validation results were documented in the aforementioned research [8].

2.3 Case studies – results and discussion

Four specimens, one for each configuration (C3 and C4) and each load case (LC1 and LC2), are discussed in this section. The relevant geometrical specifications of the joint are provided in Tab. 1, the corresponding notation shown in Fig. 2. The overall length of the beam L_b and CHS column L_c, as indicated in Fig. 2, were taken as 5000 and 2340 mm respectively. The ultimate joint strengths were calculated following the newly developed design guidelines [8].

For the LASTEICON configuration C3 under LC1, the flanges of the through-I-beam started to yield just outside the CHS column prior to all other components of the joint. This occurred due to the rigid-body behaviour of the main joint panel. Compressive stresses generated by the moments on each side of the joint panel did not affect the through-I-beam flanges in C3 thanks to the anchorage provided by the continuous web. So the fracture was triggered solely by the bending of the through-I-beam flanges just outside the CHS column surface, as evidenced by the Von Mises equivalent stresses shown in Fig. 4a. However, the through-flanges eventually reached the yield stress, thus confirming the effective transmission of the bending moments.

Tab. 1 Geometric specifications of case-study specimens

Specimen & load case	Main beam		Through-member specifications					CHS specifications		Joint strength
	IPE	L_b (mm)	h (or d_b) (mm)	b_f (mm)	h_w (mm)	t_w (mm)	t_f (mm)	d_c (mm)	t_c (mm)	V_{bu} (kN)
C3-LC1	IPE 400	5000.0	400	180	373	08.6	13.5	355.6	10.0	199.8
C3-LC2	IPE 400	5000.0	400	180	373	08.6	13.5	355.6	10.0	122.6
C4-LC1	IPE 400	5000.0	440	180	320	10.0	20.0	355.6	10.0	258.9
C4-LC2	IPE 400	5000.0	440	180	320	10.0	20.0	355.6	10.0	128.4

Similarly, for the LASTEICON configuration C4 under LC1, the through-flange-plate primarily resists the compressive stresses generated by the vertical loads applied at the extremities of the main beams. So the chances of the through-flange-plate buckling under compression remains prevalent. Contrary to the C3 connection, as the through-web-plate is not directly connected to the through-flange-plates in the C4 connection, it cannot provide anchorage to resist the through-flange-plate buckling. After the through-flange-plate buckles, the forces are redistributed to the through-web-plate via the CHS column. When the web plate reaches its capacity, it buckles under compressive stresses due to bending. Finally, ultimate failure occurs due to compressive crushing of the CHS column wall. This force transfer mechanism was observed during a detailed parametric study and was discussed in previous research [8]. However, in this study a conscious choice was made to avoid such a brittle failure in the joint by providing a suitably thick flange plate. The through-flange-plates were therefore strong enough to provide the necessary resistance and, consequently, the main beams eventually failed due to flexural plasticity just outside the main beam-to-through-flange-plate connection zone (Fig. 4b).

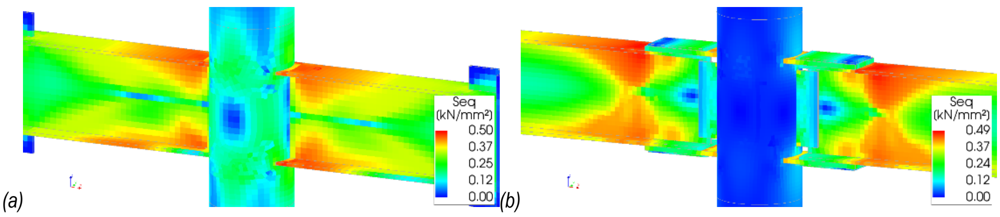


Fig. 4 Von Mises equivalent stresses obtained at failure under LC1 for a) C3-LC1 and b) C4-LC1

A different force transfer mechanism was perceived for both configurations under LC2 compared with LC1. Yielding occurred simultaneously in both the through-I-beam web (or through-web-plate) and the CHS column surface as illustrated in Figs. 5a and 5b for C3 and C4 respectively. The antisymmetric vertical loads applied at the furthest extremities of the main beams created moments in opposite directions on each side of the joint panel. These were resisted by a combination of transverse shear resistance provided by the through-member (I-beam web or web plate) and the transverse tensile/compressive resistance of the CHS chord face. As a result, the web yielded in the "passing-through" zone, with consecutive yielding of the CHS chord face surrounding the flange connection zone in tension for both configurations. Although the CHS chord provided equal resistance (analytically as well as numerically) for both the C3 and C4 configuration, a substantial difference was noticed, however, in the shear behaviour of the through-I-beam web in C3 and the through-web-plate in C4. Although the shear stresses in the through-I-beam web (C3) were seen to develop according to a uniform rectangular distribution throughout the whole section in both the vertical and longitudinal directions (flanges anchor the web thanks to a continuous link), as can be observed in Fig. 5a, the shear stresses could not distribute evenly along the vertical direction of the through-web-plate in the C4 connections, as illustrated in Fig. 5b. The shear stress distribution in the vertical direction of the through-web-plate was noticed to have a rather parabolic form instead of a uniform rectangular one. This was also combined with significant flexural stresses developing at the four corners of the through-web-plate, thus further limiting the development of the uniform shear stress distribution along the through web plate's vertical axis. So a parabolic shear stress distribution was considered in the vertical direction of the through-web-plate to design the C4 connections. As a consequence, in order to maintain equality in shear stresses according to the Cauchy Reciprocal Theorem, this phenomenon limited the development of the shear stresses in the longitudinal direction of the through-web-plate. This phenomenon and its successful realization in the design guidelines were comprehensively discussed in a previous research [8].

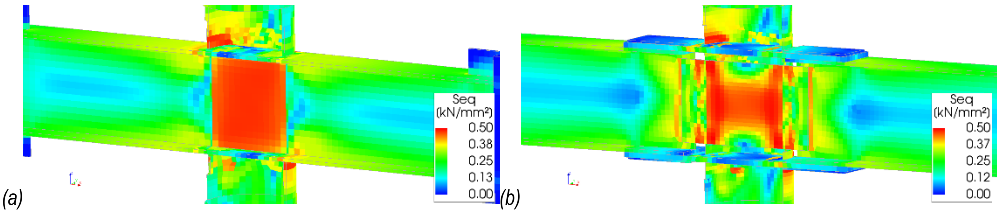


Fig. 5 Von Mises equivalent stresses obtained at failure under LC2 for a) C3-LC2 and b) C4-LC2

2.4 Comparison with conventional open-to-CHS connections

As discussed in section 1, the conventional open-to-CHS connection is not completely capable of utilizing the advantages provided by the hollow sections. In such connections the direct welding technique used to connect the I-beams to the CHS chord surface results in unavoidable local distortion at the CHS column face. Therefore, a brief comparison study was carried out in order to reveal the advantages of the proposed LASTEICON "passing-through" I-beam-to-CHS column connections over conventional connections. Conventional joint configurations – called CoC3 (Fig. 6a) and CoC4 (Fig. 6b) – with similar geometric specifications (see Tab. 1) were modelled corresponding to both LASTEICON configurations, C3 and C4, by removing the relevant "through" members only inside the CHS as shown in Fig. 6. The slots in the CHS column wall were also removed. As the failure mode in such conventional connections is generally governed by the CHS column, the CHS column thickness alone was varied to check the minimum thickness required for these conventional connections to match their corresponding LASTEICON configuration. The force-displacement curve comparisons are illustrated in Figs. 7a and 7b for C3 and C4 respectively.

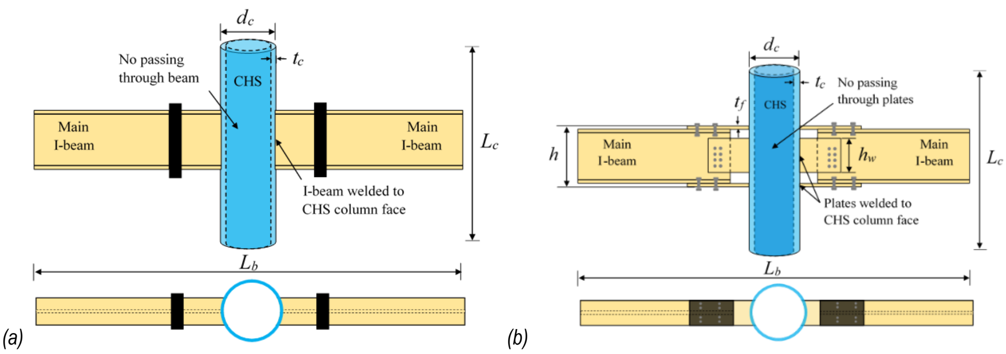


Fig. 6 Schematic diagram of conventional open-to-CHS configurations: a) CoC3 and b) CoC4

As the through-member (I-beam for C3 and flange plate for C4) solely dominates the resistance mechanism under LC1, significant advantages can be seen in the force-displacement curve comparisons shown in Fig. 7. For LC1, a CoC3 configuration with 22 mm thick CHS column provides only as much resistance as the LASTEICON C3 configuration with a 10 mm thick CHS column. An equally noteworthy advantage was noticed when the CoC4 configuration was compared with the LASTEICON C4 configuration. A significant decrease in the stiffness was also observed for the conventional joint configurations due to the removal of the "passing-through" members.

The margin was observed to be slightly lower for LC2, as a 16 mm thick column in the CoC3 configuration provides as much resistance as the LASTEICON C3 configuration with 10 mm thickness. Similarly, a 14 mm thick CHS column in the CoC4 connection was observed to provide as much resistance as the LASTEICON C4 configuration with 10 mm CHS thickness. This comparison study therefore proved that passing-through members make a significant contribution to strengthening and stiffening the joint panel and showcased a clear advantage offered by their use in the LASTEICON configurations under both loading scenarios.

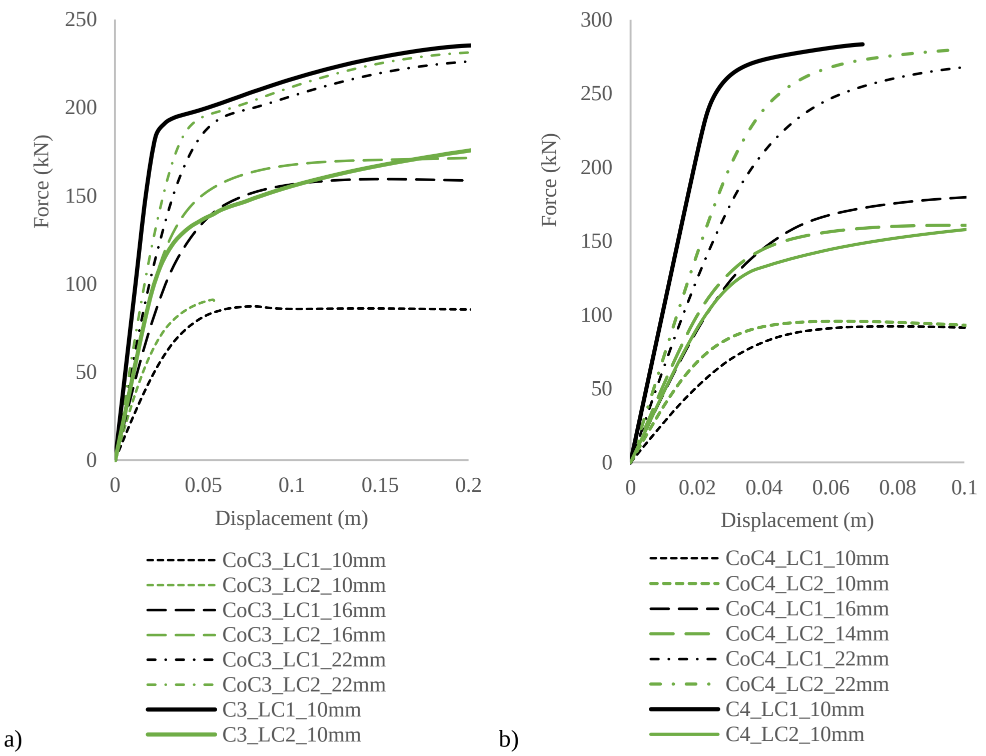


Fig. 7 Vertical force-displacement curve comparisons between LASTEICON and conventional connections: a) C3 vs. CoC3 and b) C4 vs. CoC4

3 Conclusion

This research article presented different types of LASTEICON "passing-though" two-way moment-resisting open-to-CHS joint configuration that can be effectively used in structures with predominantly gravitational as well as opposite bending loads. Relevant design procedures to calculate the resistance offered by such joints, primarily verified through a detailed numerical parametric analysis and an experimental campaign, were also referred to. For appropriately designed joints under the gravitational loading LC1, a rigid body-like behaviour was obtained in the "passing-through" joint panel. As a result, the failure was solely governed by the plastic flexural resistance of the through-I-beam just outside the CHS for configuration C3 and by the plastic flexural resistance of the main I-beam just outside the main beam-to-through-flange-plate connection zone for configuration C4. In the opposite bending loading LC2, both the through-member (I-beam for C3 and web plate for C4) as well as the CHS column contributed significantly towards resisting the moments. For properly designed joints, failure occurred simultaneously in the through-beam web (due to transverse shear) and the CHS column surface (due to transverse tensile/compressive forces). The LASTEICON configurations were also compared with their corresponding conventional configurations in order to discuss the advantages of the "passing-through" approach over the "directly welded" technique. Under LC1, a 2.2 times thicker CHS column was required for the conventional configurations to equal the resistance of a LASTEICON configuration with similar geometric/sectional properties. Under LC2, a 1.4–1.6 times thicker CHS column proved to suffice. A significant loss in joint stiffness was also highlighted in the conventional configurations due to the removal of the "passing-through" members.

Acknowledgements

This research study was possible thanks to the research fund provided by the European Commission with the contract LASTEICON EU-RFCS GA-709807 (www.LASTEICON.eu). The project consortium includes Fincon Consulting Italia srl (coordinator), RWTH Aachen, University of Pisa, Hasselt University, Instituto Superior Tecnico of Lisbon and INSA Rennes, ADIGESYS, OCAM and VALLOUREC. The cooperation of all of them is hereby gratefully acknowledged.

References

[1] Wardenier, J.; Packer, J. A.; Zhao, X. L.; Van der Vegte, G. J. (2010) *Hollow Sections in Structural Applications*. CIDECT, Geneva.

[2] Bursi, O. S. (2009) *Prefabricated composite beam-to-column filled tube or partially reinforced-concrete encased column connections for severe seismic and fire loadings*. RFSR-CT-2003-00034, final report.

[3] Wardenier, J.; Packer, J. A.; Van der Vegte, G. J.; Zhao, X. L. (2008) *Design guide for circular hollow section (CHS) joints under predominantly static loading*. CIDECT Design Guide 1, Geneva.

[4] Wardenier, J. (1995) *Semi-rigid connections between I-beams and tubular columns*. Final report, ECSC-EC-EAEC, Brussels/Luxembourg.

[5] Voth, A. P. (2010) *Branch Plate-to-Circular Hollow Structural Section Connections*. Doctoral thesis, University of Toronto, Toronto, Canada.

[6] Castiglioni, C. A.; Kanyilmaz, A.; Salvatore, W.; Morelli, F.; Piscini, A.; Hjiaj, M.; Couchaux, M.; Calado, L.; Proença, J. M.; Hoffmeister, B.; Korndörfer, J.; Bigelow, H.; Degee, H.; Das, R.; Raso, S.; Valli, A.; Brugnolli, M.; Galazzi, A.; Hojda, R. (2016) EU-RFCS project LASTEICON (Laser Technology for Innovative Joints in Steel Construction), www.LASTEICON.eu.

[7] Kanyilmaz, A.; Castiglioni, C. A. (2018) *Fabrication of laser cut I-beam-to-CHS-column steel joints with minimized welding* in: Journal of Constructional Steel Research 146, pp. 16–32.

[8] Das, R. (2019) *Earthquake resisting potential of innovative hybrid coupled shear walls with laser-cut open-to-circular hollow section connections*. Doctoral thesis, Hasselt University, Hasselt, Belgium.

[9] DIANA User's Manual, DIANA Release 10.2, May 2018.

[10] Couchaux, M.; Vyhlas, V.; Hjiaj, M. (2019) RFCS Project LASTEICON Test Report: Tests on Joints C3 and C4. Project report, INSA, Rennes, France.