

Investigation into the structural performance of passing-through plate-to-HSS 3D-cut welded joints

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ABSTRACT

Hollow Structural Sections (HSS) are an indispensable part of residential and industrial construction sectors due to their strength, efficiency, and versatility. Nonetheless, their intricate beam-to-column connections demand considerable construction effort and resources. To address these challenges, the implementation of a novel fabrication process, i.e. Laser Cutting Technology (LCT) method, has recently facilitated the production of HSS passing-through joints. This research investigates the influence of different welding techniques on the structural performance and failure mechanisms of HSS LCT passing-through welded joints (HSS-LCT-W). A comprehensive material characterization analysis, 35 monotonic tensile tests, and over 40 Finite Element (FE) simulations on a wide range of HSS-LCT-W joints with different welding and manufacturing categories were carried out. The study also seeks to derive a reliable closed-form solution to estimate the capacity of Rectangular Hollow Section LCT fillet-welded joints (RHS-LCT-FW), through the surrogate modeling and integration of the effective weld length concept. Relevant findings highlight that HSS LCT full strength fillet welded joints (HSS-LCT-FSFW) represented the most efficient solution. For partial joint penetration joint fabrication process (PJP), LCT plus milling to maintain the weld root face is a favorable procedure. Circular Hollow Section (CHS) joints are favoured over RHS joints due to their specific arch resistance mechanism against tensile loading. Certain additional procedures, such as surface oxidation removal before welding, have been demonstrated to be unnecessary. The derived capacity equation showed that an optimal design

of HSS fillet welded joints can be achieved using a reduced width for the passing-through plate or a thick column.

Keywords: HSS joint, Fillet weld, Full penetration groove weld, Partial penetration groove weld, Strength capacity, Failure mechanism, Weld effective length

Nomenclature

A_R	reduced area of the coupon specimen
A_w	weld throat area ($t_w l_w$ or $t_w l_e$)
B_e	the effective width of the plate or rectangular HSS branch
CV	coefficient of variation
C_1	plastic strain in pure shear state
C_2	plastic strain in uniaxial tension state
D	damage variable
D_c	CHS column diameter or RHS column wide
D_f	tensile failure displacement of a joint
D_y	tensile yielding displacement of a joint
$F_{y,c}$	the yield stresses of the passing-through plate
$F_{y,s}$	the yield stresses of the column
L_s	length of the passing-through plate
P_i	Coefficients of the proposed effective length equation (Eq. (6))
R_n	the nominal design strength of joints
V_u	tensile ultimate strength of a joint
W_s	passing-through plate width
f_u	ultimate tensile strength of the weakest part of the joint
l_e	weld effective length
l_w	weld true (total) length
m_R	mean ratio of actual (experimental/numerical results) to predicted nominal strength
n_o	strain hardening exponent
t_c	HSS thickness
t_s	passing-through plate thickness
t_w	throat thickness of the weld
$\bar{u}^{pl}$	softening phase plastic displacement
α	coefficient of separation (0.55)
α'	effective length factor
β	plate width-to-HSS diameter ratio (W_s/D_c)

β^{+i}	reliability index
β_w	correlation coefficient
γ	radius or width-to-thickness ratio of the HSS ($D_c/2t_c$)
γ'	angle between the planes of the effective throat thickness and the fusion face
γ_{M2}	partial safety factor (= 1.25)
$\bar{\epsilon}_o^{pl}$	plastic strain at fracture initiation
η	stress triaxiality
η_o	stress triaxiality at the central section of the coupon specimen
θ	loading angle between the weld longitudinal axis and the applied load
K	the aspect ratio of the passing-through plate (L_s/W_s)
μ	weld throat thickness to the passing-through plate ratio (t_w/t_s)
$\phi_{\beta^{+i}}$	resistance modification factor
ϕ_w	resistance reduction factor
$i_{Eurocode, RHS}$	proposed effective length equation for RHS joints compatible with Eurocode standard
$i_{Standard}$	effective length equation defined in AISC and Eurocode standards

1. Introduction

1.1. HSS applications and challenges

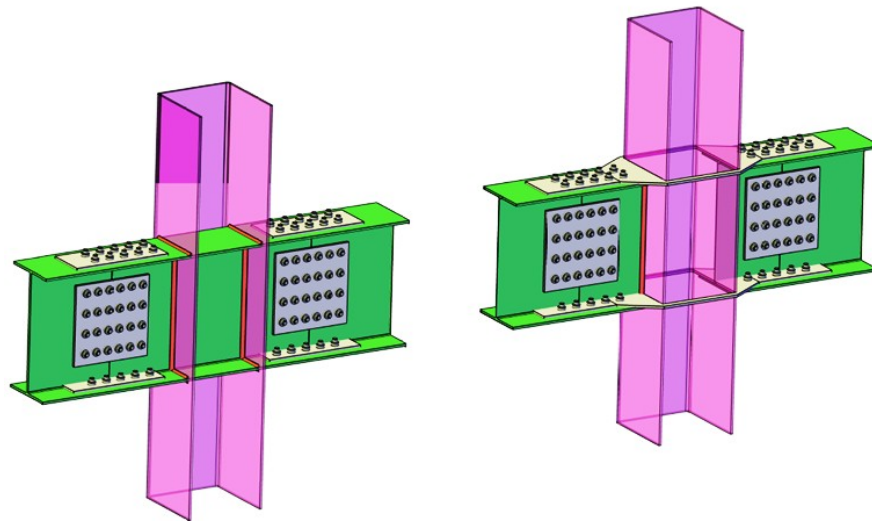
Hollow sections have been used in structural applications since the 1800s, primarily for beams, columns, and trusses [1]. They quickly gained attention among engineers and designers due to their distinguished properties including higher torsional resistance, bi-axial bending strength, and a protected inner surface against corrosive agents [1]. While I and H sections are generally cheaper per ton, RHS members are favored for benefits such as improved fire resistance and lower maintenance requirements [2]. However, one notable drawback of hollow sections compared to open web sections is limited access to their interior area along the length, to install internal reinforcement or supplementary welding or bolting. To address these challenges, various solutions have been proposed, such as relocating sizeable diaphragm connections to the external surface of the column or employing direct welded/welded stud joints on the outer face [2-4]. But most of the

proposed solutions either complicate the fabrication process by making it labor-intensive and resource demanding or lead to insufficient structural capacities.

Passing-through joints are a type of structural connection for hollow sections, where a plate or beam passes entirely through the column section. The application of these joints in structural systems offers high strength and stiffness, efficient load transfer, and reduced column thicknesses [5]. One of the commonly used RHS joints, the external diaphragm joint, is shown alongside the passing-through beam connection in Fig. 1. As illustrated, the passing-through connection creates enhanced reinforcement within the panel zone without additional reinforcements and fabrication processes.



(a) Traditional hollow section joints and the applications



(b) Laser-cut passing-through joint

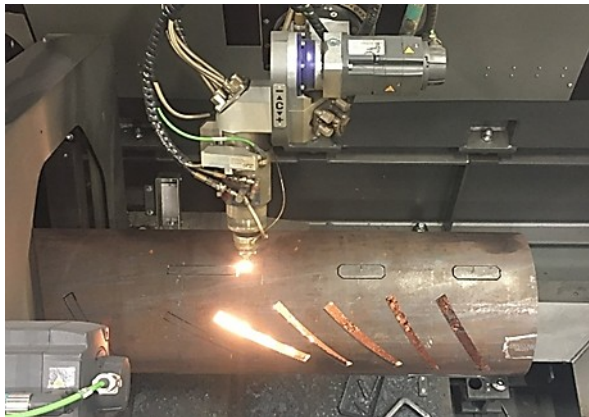
(c) External diaphragm joint

Fig. 1. Configuration of laser cutting passing through joints instead of traditional hollow section joints.

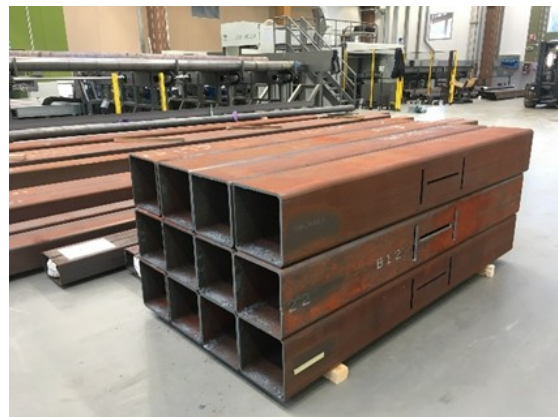
While the passing-through approach can yield promising performance results, understanding the failure modes and load transfer mechanisms in these joints requires in-depth knowledge. On the other hand, practical challenges, including cut fabrication issues and poor tolerance control, which might be associated with traditional cutting methods, remain unsolved [10].

1.2. HSS laser-cut passing-thorough joints

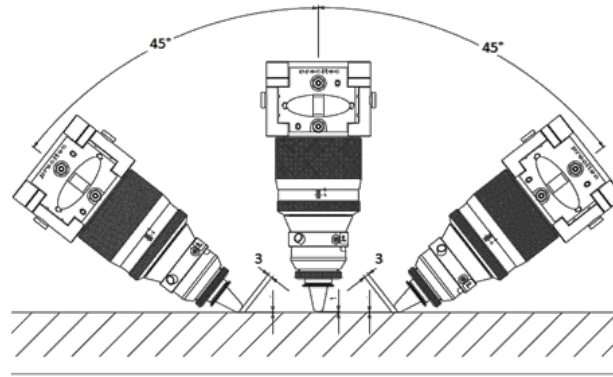
In recent years, LCT has enabled easy fabrication of HSS joints with diameters ranging from 10 to 508 mm and thicknesses up to 20 mm, in practically any desired 3D configuration [6]. As shown in Fig. 2, the laser machine operation is highly programmable, and thanks to automation, minimal operator intervention is needed [7]. The figure also demonstrates the laser machine's ability to perform cuts at angles ranging from -45° to $+45^\circ$ which allows for the creation of intricate geometries. Furthermore, compared to traditional surface treatment and cutting techniques such as plasma and oxyfuel cutting, milling, and drilling, the LCT facilitates the creation of narrow yet high-quality cuts with by minimal HAZ and the reduced surface damage [8, 9].



(a) Laser machine automation



(b) RHS with cuts in a factory setting



(c) Inclination angle of the laser-cut nozzle

Fig. 2. Laser cutting operation on hollow sections.

LCT perfectly complements the fabrication of HSS passing-through welded joints, streamlining their integration into factory-based production processes. In recent years, the manufacturing of these joints has gained significant attention. Kanyilmaz [10] reported that LCT has an untapped potential to simplify the fabrication of HSS joints while reducing both costs and material waste. Owing to its advantages, such as reduced human error, enhanced precision and quality, and a more environmentally friendly process, LCT was reported as an efficient option than traditional cutting methods. In a comparative study on open sections-to-CHS joints, Das et al. [5] demonstrated that the implementation of the passing-through method can potentially increase the strength of directionally welded connections by more than twofold. Furthermore, using a cradle-to-site life cycle assessment, the authors identified the LCT passing-through technique as a more sustainable alternative, offering up to approximately 30% improvement in sustainability for multistorey structures under both high and low seismic conditions.

Welded HSS girders with K joints are among the most common truss frames, which have been used in critical infrastructure such as bridges, stadiums, and marine structures. However, the joints can be more complex regarding load distribution, excessive welding requirements, and detailing challenges during installation [7]. In an experimental study, Menghini et al. [7] performed 31

Warren and Pratt truss girder tests, each fabricated using LCT and featuring two distinct passing-through joint geometries. Although the Warren type with LCT joints demonstrated a strength increase of 20% compared to conventional equivalents, the study underscored the strong dependence of the failure behavior of the joints on geometric characteristics, highlighting LCT significant potential for future optimization of the joint's topology. In other experimental/numerical studies undertaken by [7, 11, 12], the key parameters affecting the response of HSS LCT passing through joints given plastic failure mechanisms and yield lines have been identified which leads to a set of analytical equations for predicting both the strength and stiffness of the joints. To address the limited attention given to welding capacity and the associated failure mechanisms in the previous research, Safaeifaegh et al. [13, 14] conducted a series of experimental tests and numerical parametric studies to investigate various aspects of CHS passing through welded connections to cover the failure mechanisms, stress/strain distribution, and the capacity of the joints. The authors concluded that fillet-welded passing-through connection represents a more efficient welding solution over CJP.

1.3. HSS fillet welded joint capacity evaluation

HSS joints are typically designed using one of two methods: (i) the capacity method, where the welded joint sustain the development of the full strength of the connected member, or (ii) the fit-for-purpose method, which involves designing the weld to resist only the actual applied loads, as permitted by EN 1993-1-8:2005, Section 7.3.1(6) [15]. The latter approach often results in smaller weld sizes and a partially effective weld. Newcomb and Tousignant [16] used a rational geometrical modification to convert the already introduced effective length formulation, developed by [17] for CHS-to-CHS X-connections, for application to CHS-to-plate connections. Their proposed equations estimate the CHS fillet welded joints' capacity while the plate does not pass

through the chord member. Safaeifaegh et al. [14] proposed a couple of closed-form expressions for estimating the capacity of the CHS passing through fillet welded joints, grounded in the concept of effective fillet length, due to the limitations identified in the equations proposed by [16]. Madhouni et al. [18] performed experimental and numerical investigations on the failure mechanism of "passing-through I-plates-to-square hollow section (SHS) joints" under gravitational loading to integrate the rotational stiffness and bending capacity of the joint into the component method; however, their approach does not account for weld fracture as a distinct component.

Despite recent advancements, there remains a gap in knowledge regarding certain production aspects, such as the use of cost-effective PJP butt welds and the influence of RHS column topology on joint performance. Moreover, apart from the equations provided in standards [15, 19] related to the effective width length of attached plates, there is a lack of research that consists of closed-form expressions for the capacity of RHS fillet-welded joints. This paper, therefore, investigates the untapped potential of HSS-LCT-W joints to broaden their applications through over 75 laboratory tests and numerical simulations. The study mainly compares two different CHS and RHS configurations and three welding processes, FSFW, CJP, and PJP. Additionally, comparison among some practical aspects such as oxidation removal before welding and multi-pass welding procedures are carried out. Finally, FE simulations, validated against experimental data, contribute to parametric study, stress analysis, and ultimately aid in the development of design recommendations and capacity equations for the RSH fillet welded joints.

2. Experimental program

The experimental workflow, including material characterization and tensile test details, is presented in this section. In addition to the 26 newly tested specimens, 9 CHS specimens from the

previous test campaign conducted in the previous test campaign [14], are also incorporated into the comparative evaluation. As a general overview shown in Fig. 3, the specimens are categorized according to two RHS and CHS column configurations, each with two different thicknesses of 10 mm and 12.5 mm.

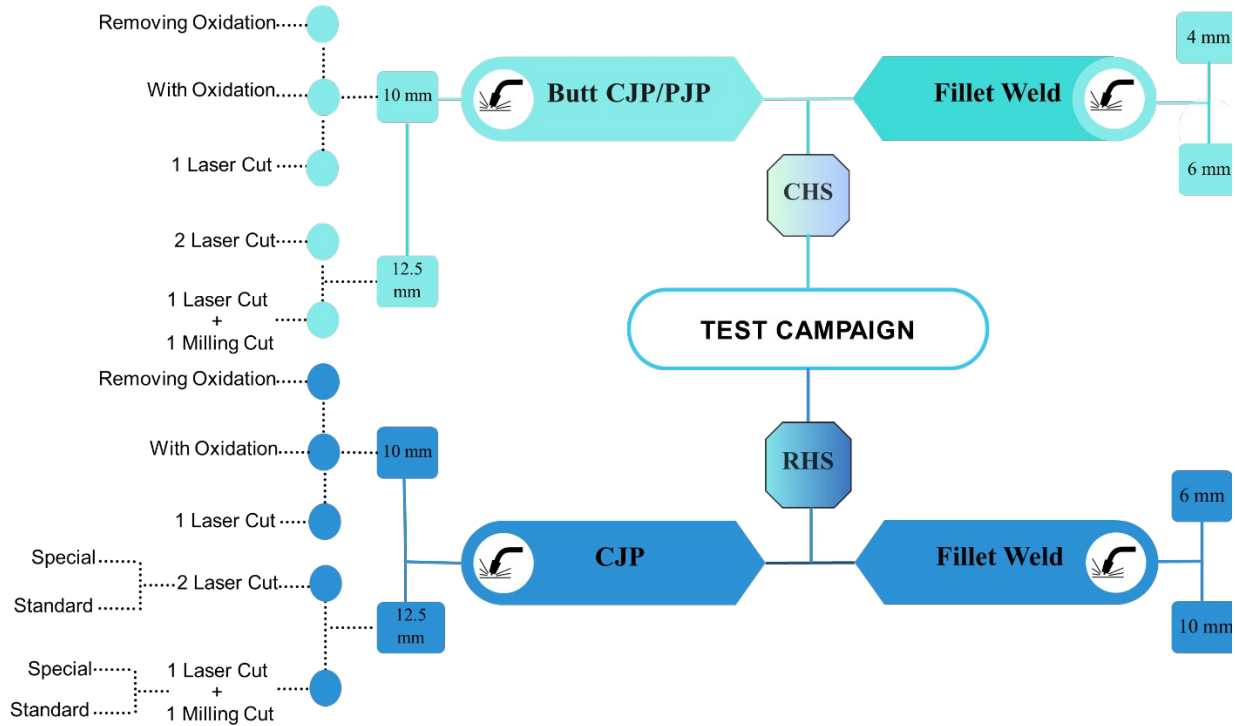


Fig. 3. The overview of the test campaign.

The test program is organized into the main categories in terms of welding techniques, including fillet weld, CJP, and PJP joints. Additional subcategories, reflecting specific production procedures, consist of two double-cut types of PJP joint (to preserve the weld root face), the necessity of oxidation removal before welding, and the use of a multi-pass welding process. Each subsequent subsection provides an overview of the relevant category.

2.1. Tests on materials

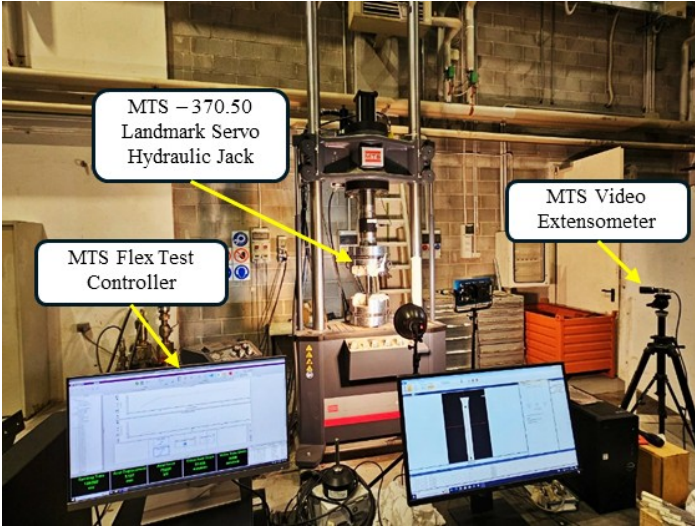
The joints were fabricated using S355 steel, with material properties verified through the manufacturer's certifications. Welding was performed using the Gas Metal Arc Welding (GMAW)

process, designated as Reference No. 135 – MAG. The filler material conformed to EN ISO 14341 [20], specified as G42-4-M21-3Si1, where “G42” denotes a 420 MPa strength electrode and “M21” indicates a shielding gas composition of 80% Argon and 20% CO₂. A wire diameter of 1.2 mm was used during the welding process. Table 1 presents the elemental composition of the electrode.

Table 1
Chemical composition of the welding electrode.

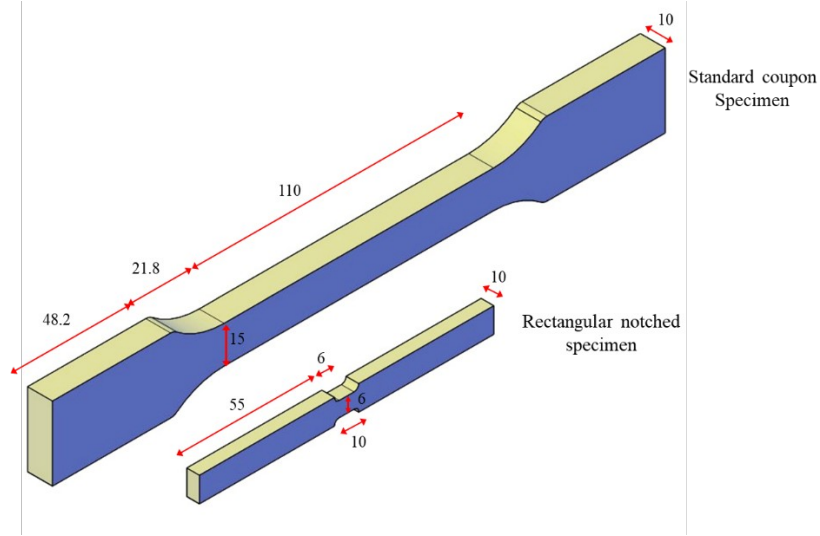
C	Mn	S	P	Si	Cu	Al	Mo	Ni	Cr	As	Ti	V	Nb
0.8	1.48	0.011	0.006	0.884	0.03	0.002	0.004	0.013	0.02	0.001	0.001	0.004	0.0021

The dimensions and characteristics of the test specimens are consistent with those shown in Fig. 4(c), including standard coupon specimens and short rectangular-notched specimens for the base metal and the welding material, respectively. The S355 base metal was machined into standard tensile coupon specimens in accordance with UNI EN ISO 6892-1[21]. The choice of short rectangular-notched specimens for testing the weld material, as recommended by [22, 23], was made to ensure crack propagation within the welded gauge length. Material testing was performed using an MTS jack equipped with a 370.50 Landmark Servo-Hydraulic System, capable of a 150 mm stroke and a maximum load capacity of 500 kN. The MTS video extensometer, a non-contact optical measurement system, was used to track and measure strain in the notched zone during testing. The MTS FlexTest also manages the servo-hydraulic jack and video extensometer system simultaneously, as shown in Fig. 4.



(a) Test setup at the laboratory

(b) Fractured coupon specimens.



(c) Dimensions of the coupon specimens

Fig. 4. Coupon test details to characterize materials' properties.

The mechanical properties obtained for the CHS/RHS column, the passing-through plate, and the welding wire material were in good agreement with the manufacturers' certifications, as illustrated in Fig. 5 and summarized in Table 2.

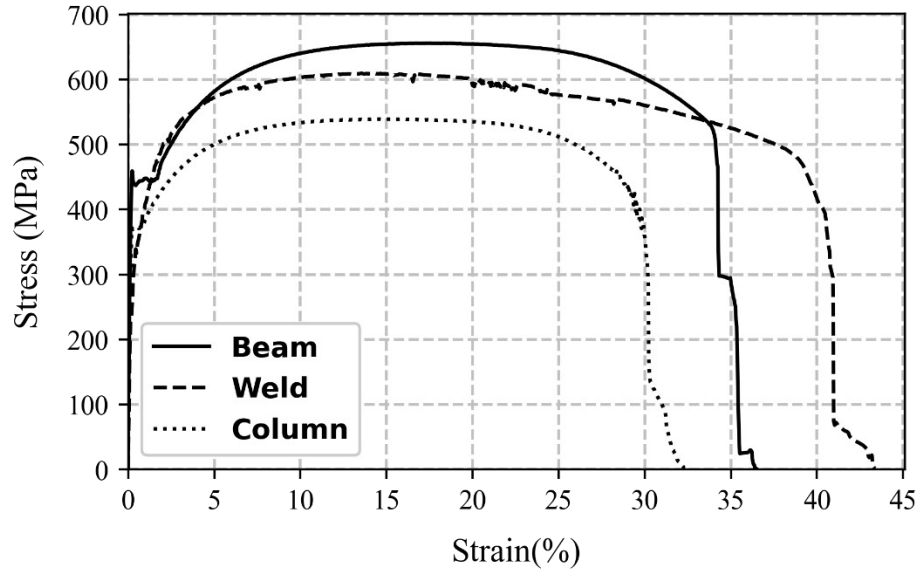


Fig. 5. Stress–strain responses obtained from the coupon test of the materials used in the joint specimens.

All coupon specimens fractured within the notched region during testing, as depicted in Fig. 4(b). The demonstrated average curves will serve as a material benchmark throughout this study.

Table 2
Material test results.

Member	Number of tests	Material	f_y when $0.2\%\epsilon$	f_u	Total elongation	Gauge length
Column	4	S355	367.13 MPa	538.94 MPa	29 %	50 mm
Stub	4	S355	436.39 MPa	655.84 MPa	34 %	50 mm
Weld	4	AWS ER70S-6	370.00 MPa	609.41 MPa	39 %	5 mm

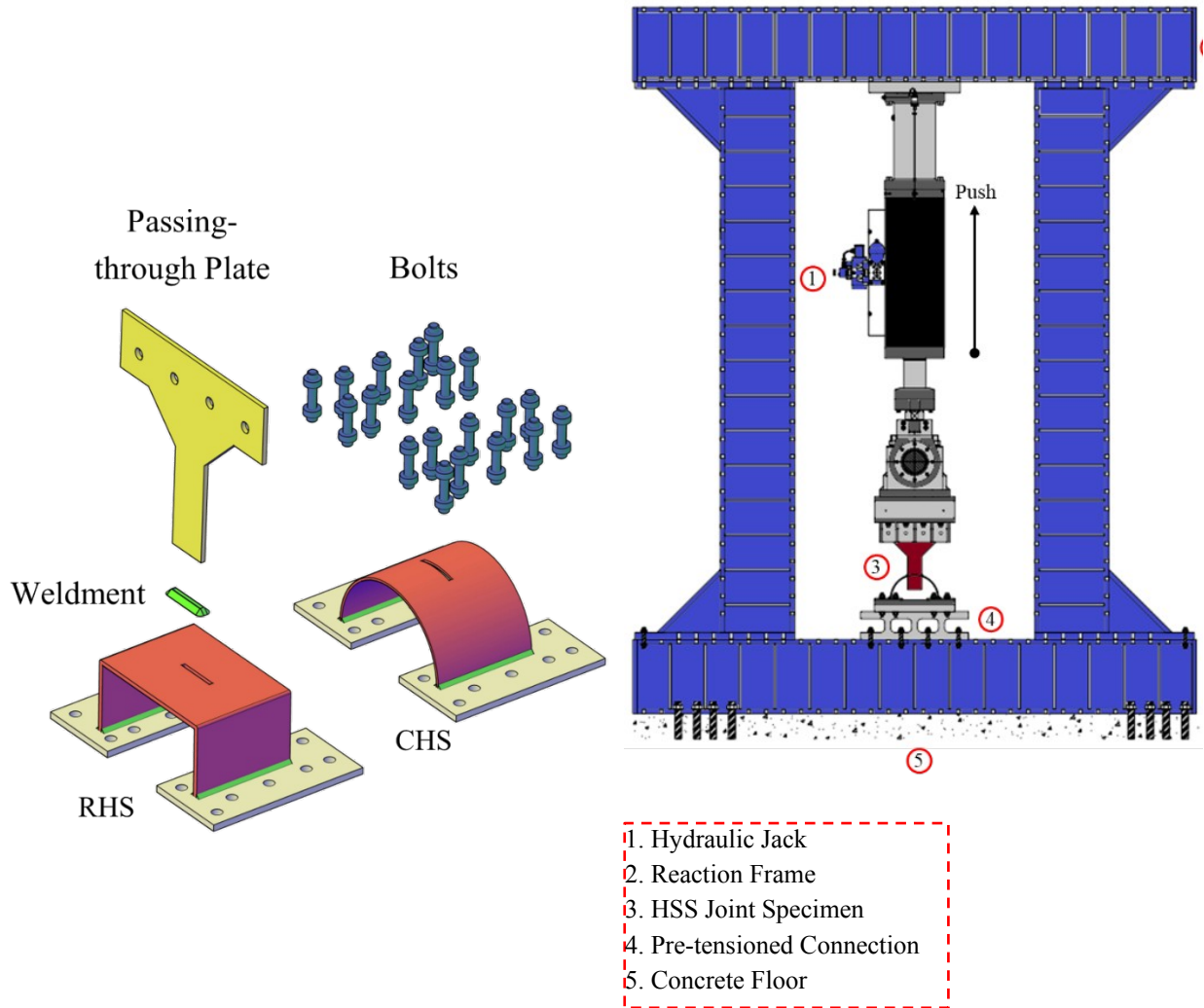
2.2. Monotonic tensile tests on HSS-LCT-W joints

This section describes the key stages of the testing procedure, including preparation, quality control, and instrumentation setup for the HSS joint specimens. Then it concludes with a systematic comparison of the experimental findings across all the defined categories.

2.2.1. Test set-up details, quality control, and sensor installation

All HSS specimens were pre-cut using LCT and welded under a manufactory condition. The joints were then subjected to quasi-static tensile testing in a displacement-controlled mode using a

MOOG actuator. This laboratory apparatus, shown in Fig. 6(b), is capable of ± 1000 kN load and ± 250 mm stroke, operating at a constant rate of 1 mm/min.



(a) HSS joints' components

(b) Test set-up details

Fig. 6. Test set-up at the laboratory.

The rate, due to the significant deformation and flexibility of RHS columns relative to CHS ones, was set to 2 mm/min to minimize the overall RHS specimens' testing time. The components of HSS-LCT-W joints are separately illustrated in Fig. 6(a). To eliminate any minor bolt slippage at the specimen's bottom connection, potentially affecting the joint's vertical movement and the test results, a pre-tensioning task was performed prior to each test using a torque meter, as illustrated in

Fig. 7(a). Additionally, a horizontal displacement restrictor was installed on all specimens to minimize unintended lateral movement at the bottom bolted connection to the frame. During the production quality control process, using Non-destructive testing (NDT) methods is essential. Three standard techniques, penetrant testing, magnetic particle testing, and ultrasonic testing, were employed to evaluate the quality of the different welded joints. Penetrant testing, applied during the preparation phase as shown in Fig. 7(b), is an effective and economical surface inspection technique for detecting surface discontinuities. This technique was used to check the fillet welds on both FW and CJP joints, where in the latter served as reinforcement weld. For a more accurate check and in agreement with the standard [24], magnetic particle testing was conducted on fillet welds to detect near and subsurface flaws, as shown in Fig. 7(c).



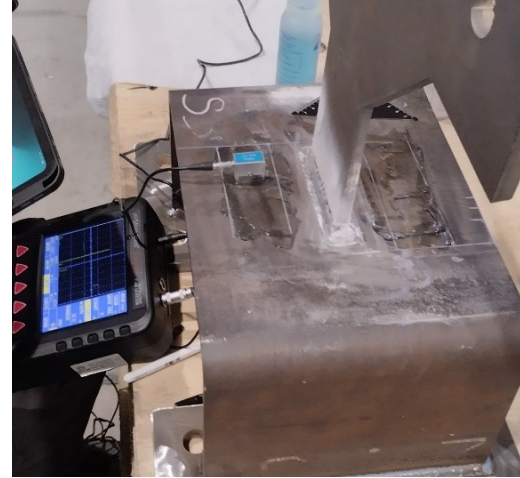
(a) Pre-tensioning of the bottom connection to the frame



(b) Spray penetrant testing



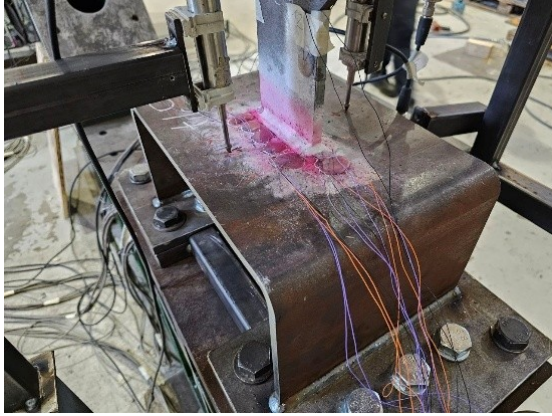
(c) Magnetic testing



(d) Ultrasonic testing

Fig. 7. Preparation and inspection of HSS joints before tests.

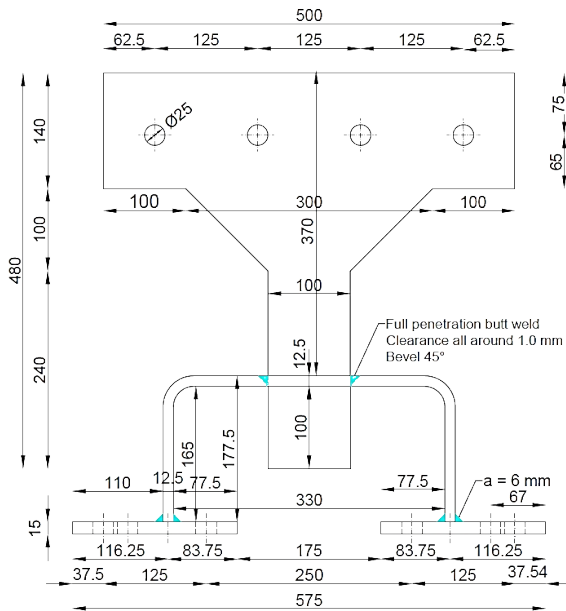
Ultrasonic testing, as required by the standard [24], was applied to CJP joints to detect internal cracks, porosities, and lack of fusion. As per the welding provider's certifications, the CJP weld was performed as a single-sided, fully penetrating groove weld with a 45-degree chamfer. The standard welding procedure (excluding special subcategories) involved an initial pass to fill the root of the bevel, followed by a secondary pass to completely fill the bevel gap between the hollow section column and the passing-through plate. This process results in an additional reinforcement layer on the outer surface of the CJP joints. The fillet joint presented in Fig. 8(a) is a T-type joint welded only on the external face of the column using different theoretical throat thicknesses. The throat thickness of all specimens was measured before testing to determine the actual weld's throat dimension in each specimen, as displayed in Fig. 8(b). A 1 mm gap was intentionally considered between the passing-through plate and the inner face of the hollow section column in all specimens, enabling the weld to partially penetrate (almost 2 mm) the base material, and enhance fusion quality. The configuration and typical dimensions of RHS and CHS joints are presented in Fig. 8(c) and (d), respectively.



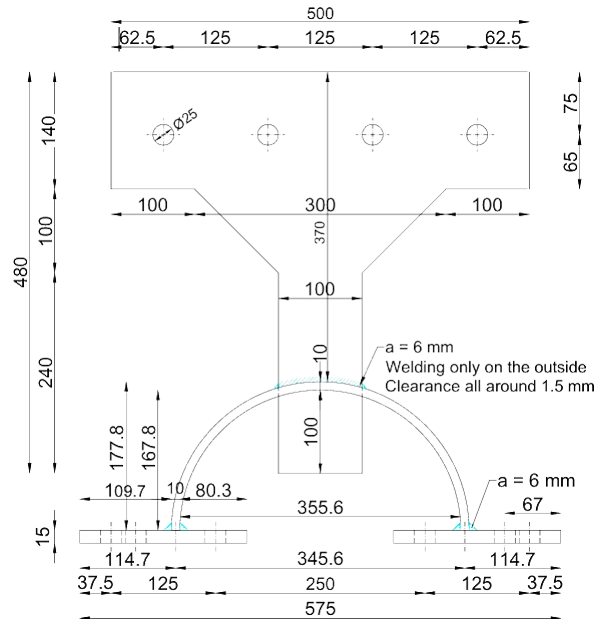
(a) RHS-LCT-FSW specimen ready for the test



(b) Measuring the actual throat thickness of the RHS-LCT-FSW joint



(c) RHS joint geometry

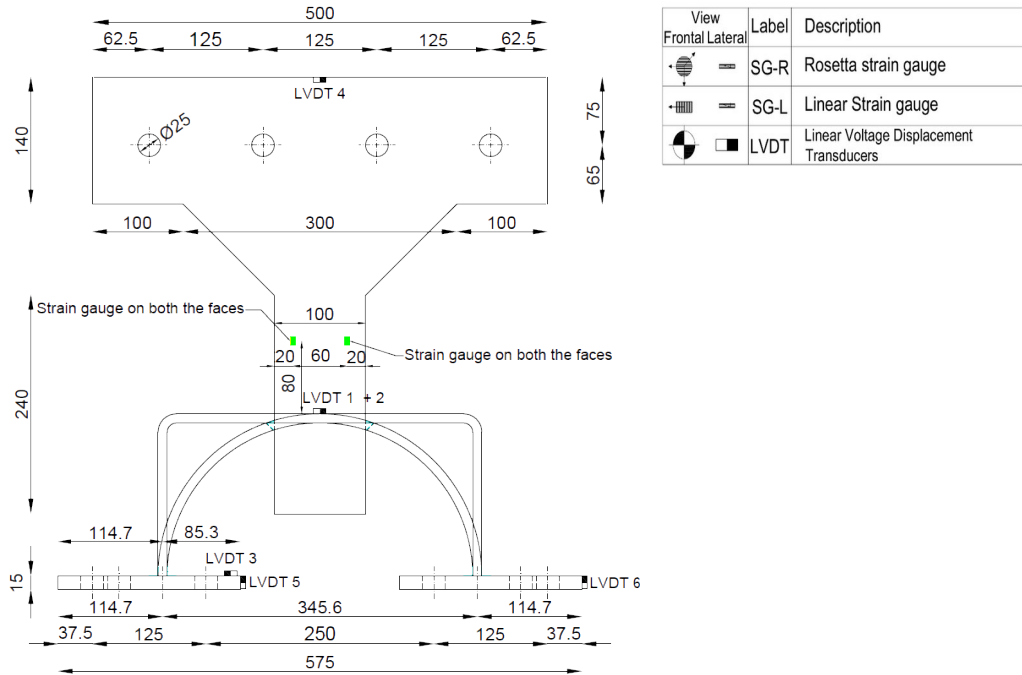


(d) CHS joint geometry

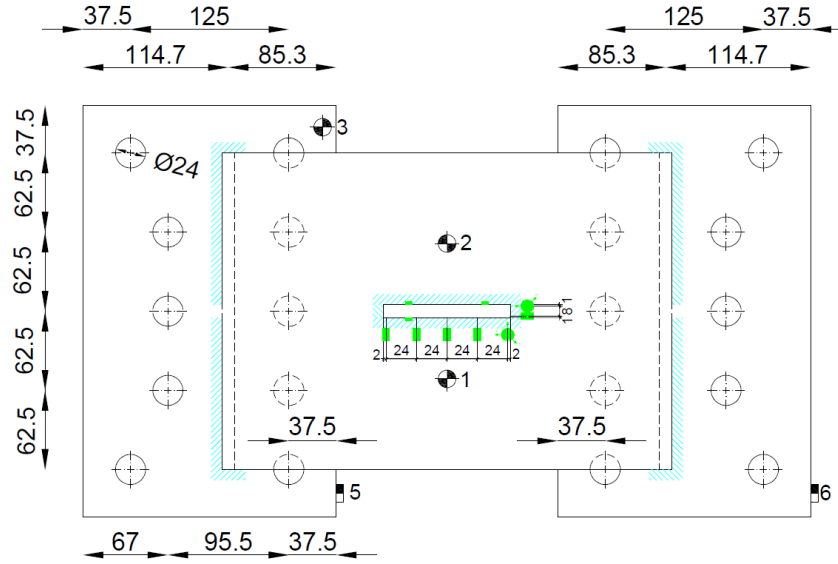
Fig. 8. HSS-LCT-W specimens' preparation, check, and geometry.

The PJP weld was also executed as a single-sided partial penetrating groove weld chamfered at a 45-degree. The HSS PJP welded specimens (HSS-LCT-PJP) were produced in a factory setting considering a 2 mm weld root face, applied through two different manufacturing processes, i.e., laser cut and milling. The subsequent subsections will provide a detailed discussion on their implementation. To ensure that the sub-assembly accurately reflects the actual performance of

beam-to-column connections and to also collect data about the performance and fracture mechanisms of the joints, 10 Strain Gauges (SGs) and 6 Linear Voltage Displacement Transducers (LVDTs) were installed strategically on each specimen, as illustrated in Fig. 9. Rosette (SG-R) and linear strain gauges (SG-L) were installed on the column and the passing-through plate, as displayed by circular and rectangular shapes in the figure. To verify the specimen's symmetry and to assess the presence of parasitic bending moments caused by imperfections, four symmetrically arranged SG-Ls were installed on the passing through plates. Additionally, four SG-Ls were devoted to record the strain distribution and identifying failure locations near the welded joint in accordance with the expected non-uniform distribution [14]. The SGs were positioned approximately 80 mm above the weld toe to avoid the high-strain region near the weld influenced by the notch effects [3]. The first pair of LVDTs (LVDT-1 and LVDT-2), were used to track the outward displacement on the outer surface of the column and to check the symmetry of the joint's response.



(a) Front view of sensor arrangement

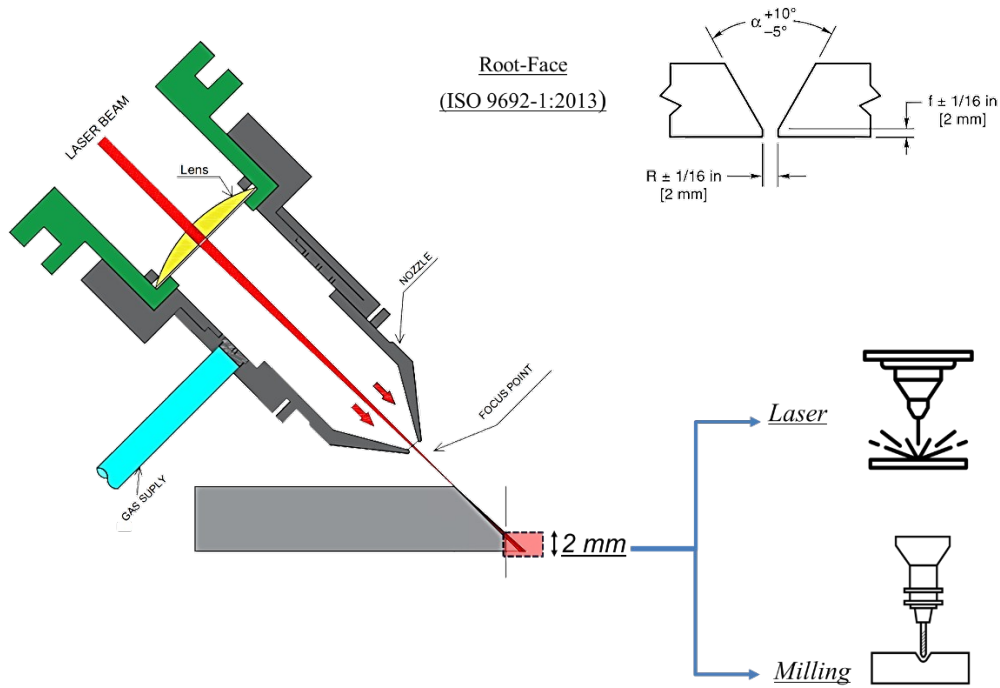


(b) Plan view of sensor arrangement
Fig. 9. Sensors installation on HSS specimens.

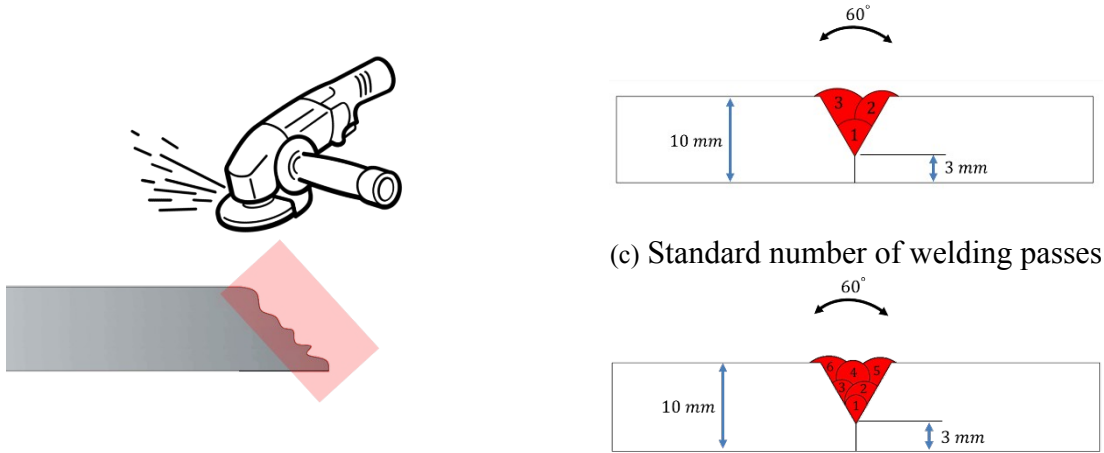
LVDT-3 and LVDT-4 measure the specimen's axial displacement at the top and bottom of the sub-assembly to eliminate the influence of the reaction frame's compliance along the actuator axis. LVDT-5 and LVDT-6 monitor minor and redundant horizontal shifts at the lower bolted joint caused by potential bolt slippage.

2.2.2. Investigated subcategories and classification of HSS-LCT-W tested joints

In this subsection, attention is given to explaining a couple of activities that are either important in industrial applications or procedures outlined in standards. The first sub-category is applied to PJP joints, where the execution of the initial inclined cut is performed by laser, and the following vertical cut is conducted with either laser or milling procedure, as depicted in Fig. 10(a). The weld root face size in PJP welding is crucial as it controls penetration quality, proper weld stress distribution, and also has a strong influence on the fatigue life of the joint [25]. A proper welding process with a sufficient weld root face minimizes defects and incomplete fusion, particularly in curved kerfs typical of CHS joints.



(a) PJP root face cut with different processes



(b) Grinding the surface of joint before welding

Fig. 10. Second experimental campaign subcategories.

The final subcategory differentiates two welding procedures based on the number of welding passes, as shown in Fig. 10(c) and (d). The Standard welding type typically involves 2–3 passes, whereas the Special welding type requires 6 passes. The objective is to determine whether increasing the number of passes significantly improves the joint performance and quality or merely

results in higher production costs and longer time. This issue is reflected in some of the PJP specimens listed in Table 3. A total of 26 newly tested specimens, plus the 9 CHS specimens from the previous test campaign [14] (Specimen C5-A to C7-C), are summarized in Table 3.

Table 3
HSS-LCT-W joint specimens' characteristics.

Label	Column type	Column thickness	Weld (Type/Throat thickness)	Cut number (Laser + Milling)	Grinding	V_u (kN)
S3-A	RHS	12.5	PJP (Special)	2 (1+1)	Yes	497.6
S3-B	RHS	12.5	PJP (Special)	2 (1+1)	Yes	483.4
S4-A	RHS	12.5	PJP (Special)	2 (2+0)	Yes	476.6
S4-B	RHS	12.5	PJP (Special)	2 (2+0)	Yes	434.5
S7-A	RHS	12.5	PJP	2 (1+1)	Yes	504.5
S7-B	RHS	12.5	PJP	2 (1+1)	Yes	484.7
S8-A	RHS	12.5	PJP	2 (2+0)	Yes	464.2
S8-B	RHS	12.5	PJP	2 (2+0)	Yes	450.6
S13-A	RHS	10	CJP	1	Yes	362.1
S13-B	RHS	10	CJP	1	Yes	359.8
S14-A	RHS	10	CJP	1	No	356
S14-B	RHS	10	CJP	1	No	354.5
S17-A	RHS	10	FW (10 mm)	1	Yes	397.8
S17-B	RHS	10	FW (10 mm)	1	Yes	388.5
S18-A	RHS	10	FW (6 mm)	1	Yes	338.2
S18-B	RHS	10	FW (6 mm)	1	Yes	350.3
C0-A	CHS	10	FW (10 mm)	1	Yes	531.5
C0-B	CHS	10	FW (10 mm)	1	Yes	529
C1-A	CHS	10	CJP	1	Yes	430.1
C1-B	CHS	10	CJP	1	Yes	393
C2-A	CHS	10	CJP	1	No	408.6
C2-B	CHS	10	CJP	1	No	403.9
C3-A	CHS	12.5	PJP	2 (1+1)	Yes	463.1
C3-B	CHS	12.5	PJP	2 (1+1)	Yes	434.3

C4-A	CHS	12.5	PJP	2 (2+0)	Yes	418.6
C4-B	CHS	12.5	PJP	2 (2+0)	Yes	425.8
C5-A	CHS	10	FW (4 mm)	1	Yes	273.9
C5-B	CHS	10	FW (4 mm)	1	Yes	284.9
C5-C	CHS	10	FW (4 mm)	1	Yes	282.1
C6-A	CHS	10	FW (6 mm)	1	Yes	365.6
C6-B	CHS	10	FW (6 mm)	1	Yes	362.3
C6-C	CHS	10	FW (6 mm)	1	Yes	348.9
C7-A	CHS	10	CJP	1	Yes	400.6
C7-B	CHS	10	CJP	1	Yes	428.7
C7-C	CHS	10	CJP	1	Yes	442.5

* FW is an acronym for fillet weld

2.2.3. Tensile tests results

This section presents a comprehensive comparison among specimen groups, each characterized by distinct features. The joints under monotonic tensile loading typically experience plastic deformation, crack propagation, and ultimate failure, without the occurrence of sudden global or local instabilities such as buckling induced by compressive forces. Consequently, geometric imperfections have a minimal impact on the specimens' ultimate capacity. In addition, weld failure mode predominantly governs the loss of capacity at the peak point in all RHS-LCT-FW specimens. To investigate and compare the test results and failure mechanisms of the HSS joints, the final stage of the experimental tests for an FSFW joint, a PJP joint, and a CJP joint are presented in Fig. 11. As noted in [14, 26-28], a highly non-uniform stress distribution around the welded joints, resulting from insufficient rigidity and difference in flexibility of HSS joints, leads to stress concentration and localized failure first at the corners, as observed in the figure. Following crack initiation at the corners, the fracture propagated along the longitudinal section of the weldment until ultimate failure occurred. However, in some specimens, such as the CJP joints with a robust weld reinforcement, the crack extended beyond the weld, propagating onto the column face and forming

a triangular failure pattern, consistent with the observations reported in [14]. The failure at the ultimate strength of the joints was abrupt and accompanied by a loud bang.

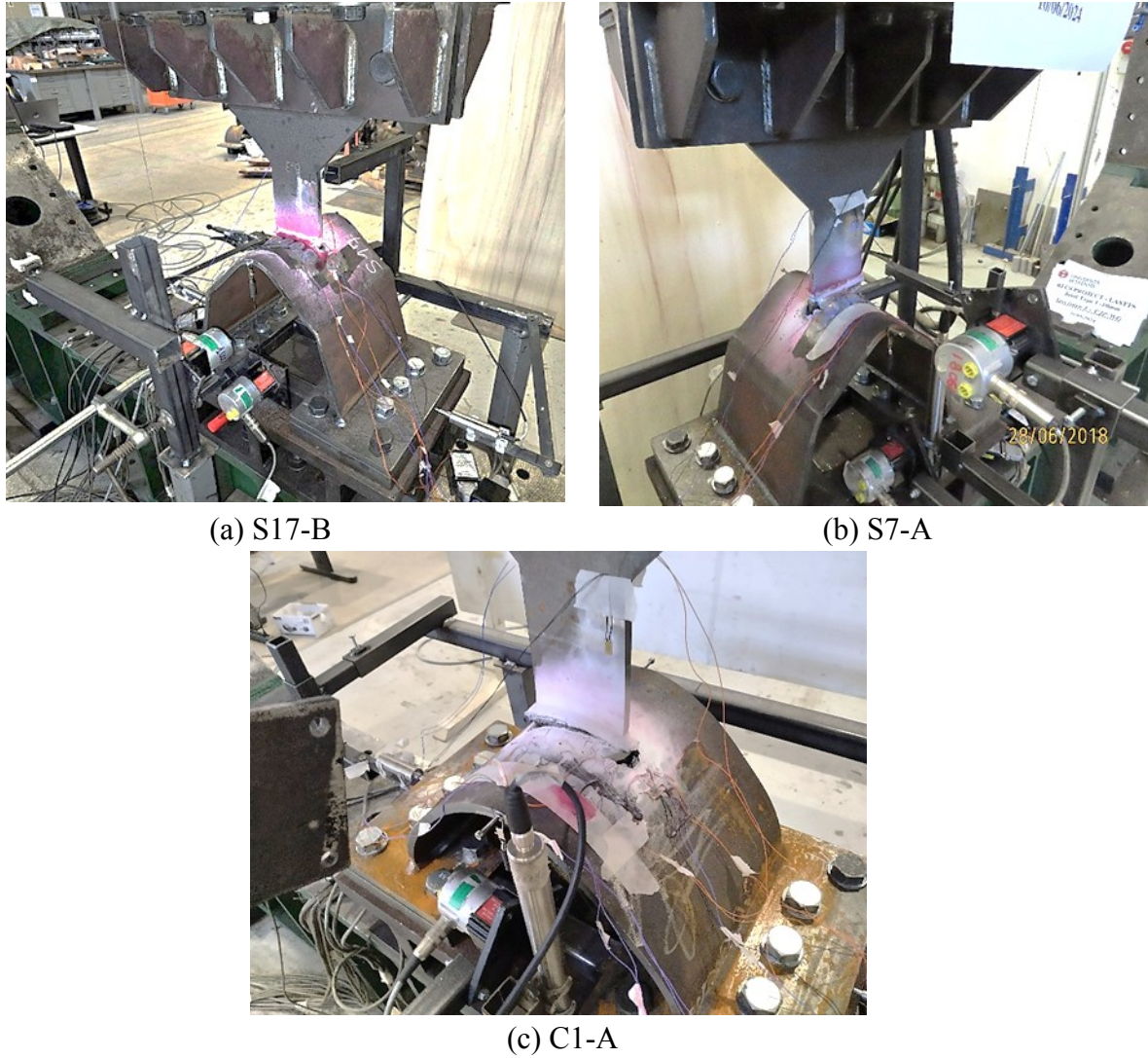


Fig. 11. Fracture observed in some HSS-LCT-W specimens during testing.

As the first comparison group, a general assessment is conducted between two column shapes: RHS and CHS sections. This comparison focuses on CJP and fillet weld joints with a nominal throat thickness of 6 mm, without considering penetration depth. All joints share identical geometric parameters and material properties. Fig. 12 shows that CHS joints outperform RHS joints owing to exhibiting nearly twice the initial stiffness. This stiffness advantage is evident in both the elastic and plastic phases, while the difference in ultimate strength remains marginal.

These differences arise from the distinct deformation mechanisms of the hollow sections under tensile forces. As illustrated in Fig. 12(c), the deformation of RHS joints can be approximated as a frame with two roller supports at the upper intersections, which is comparatively flexible against the tensile loading. On the other hand, as shown in this figure, CHS joints benefit from an inherent arching action mobilizing against the tensile loading, which is enabled by their circular geometry. This deformation pattern transforms the curved profile of the CHS joint into a triangular form, generating two inclined struts that effectively activate the column's strength against tensile forces.

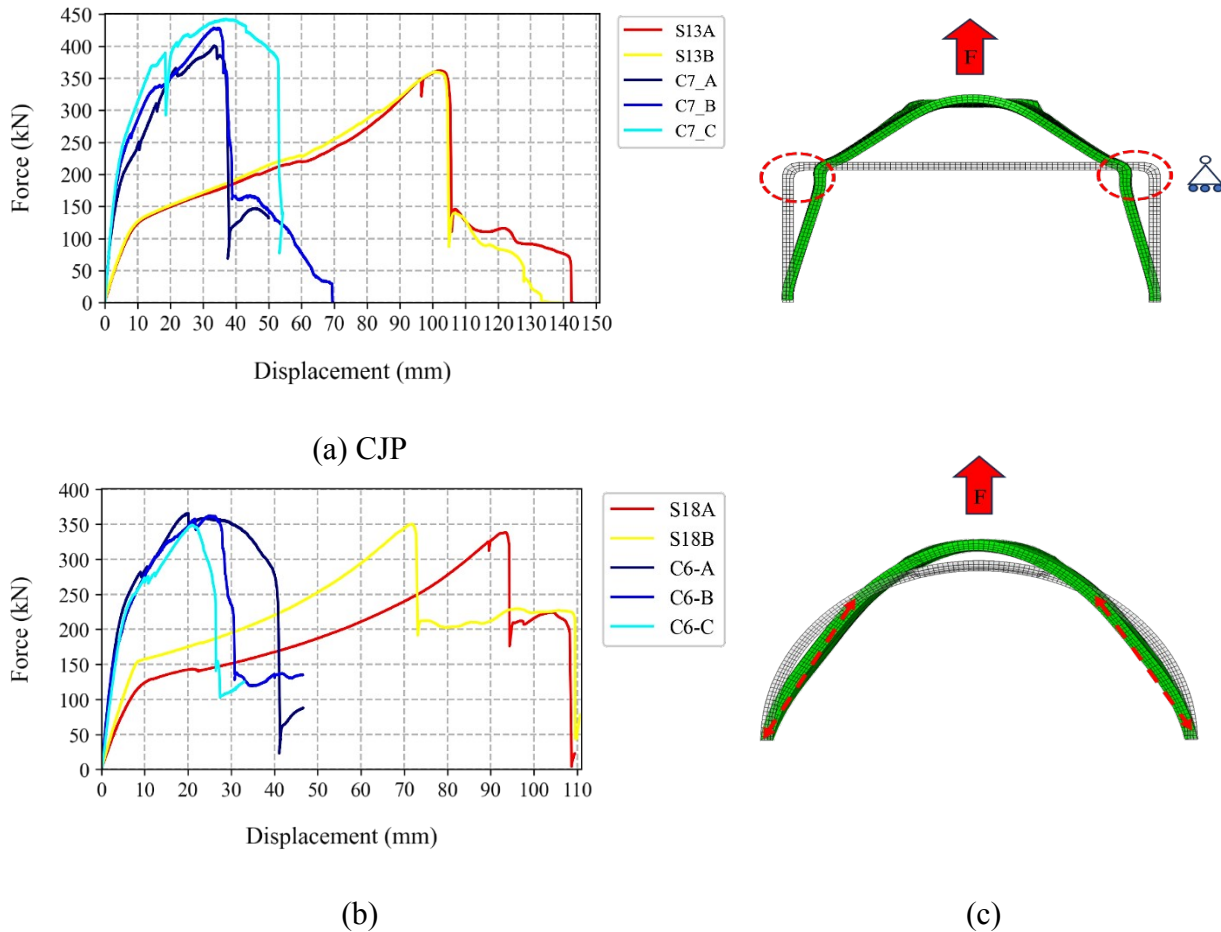
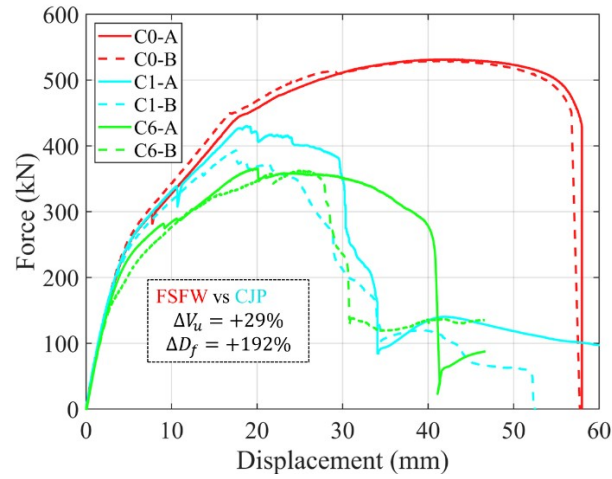


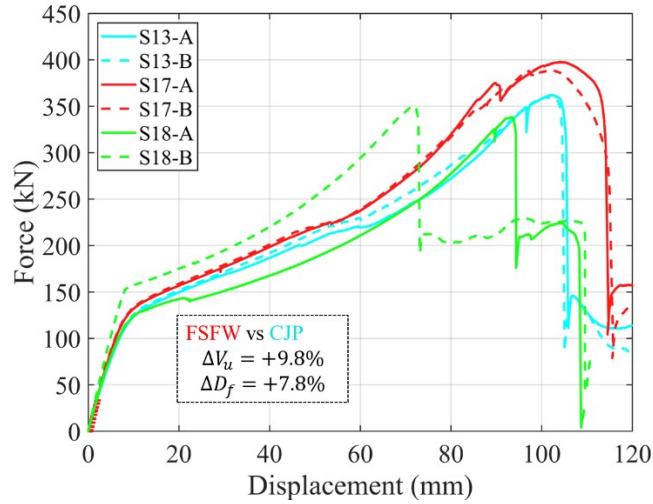
Fig. 12. Comparison of RHS and CHS configuration effects.

This deformation mechanism is independent of the boundary conditions, as simulations of full-section RHS and CHS models led to similar results. In contrast to some CHS specimens which

experienced post-failure flat zones (such as C7-C and C6-A in Fig. 12), RHS joints exhibited a sudden and sharp reduction in the capacity following the ultimate strength point. The primary focus of this section is to compare welding techniques for HSS-LCT-W joints to identify the superior process. To this end, force–displacement results of HSS joints fabricated using different welding techniques are illustrated in Fig. 13.



(a) CHS joints



(b) RHS joints

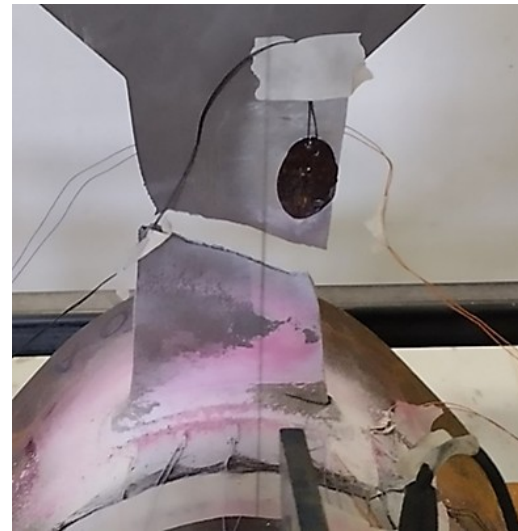
Fig. 13. The comparison between different welding on the performance of HSS-LCT-W joints.

From the results, it is evident that FSFW joints demonstrate superior performance in terms of ultimate capacity, ΔV_u , ductility, and secant stiffness, provided that high production quality and

standard welding procedures are maintained. Moreover, fillet-welded joints eliminate the need for the additional cutting and preparation processes required for CJP joints. Since the yield point is nearly identical across all joints in Fig. 13, variations in the ultimate displacement, ΔD_f , and the corresponding ductility ratio, defined as the ratio of ultimate to yield displacement, $\Delta D_f/\Delta D_y$, further highlight the advantages of FSFW joints. Notably, fillet-welded joints with a 6 mm throat thickness (green curves), also exhibit comparable capacities to CJP joints with differences ranging between 4% and 8%. As shown in Fig. 14, the failure mode of the C0-A and C0-B FSFW specimens was characterized by the tearing of the passing-through plate before the complete failure of the welded joint. Notably, these two specimens were the only ones in which the passing-through plate reached its ultimate capacity before weld failing.



(a) Initiation of failure and stress concentration on the corners

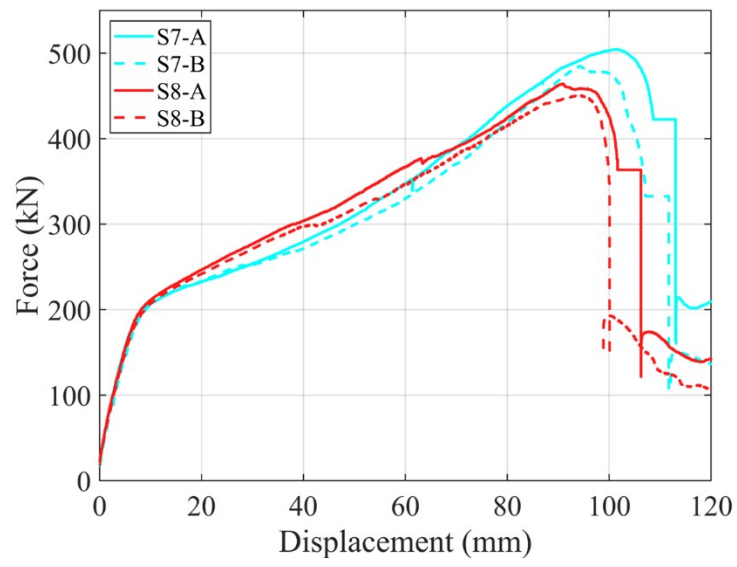


(b) Breakage of the passing-through plate

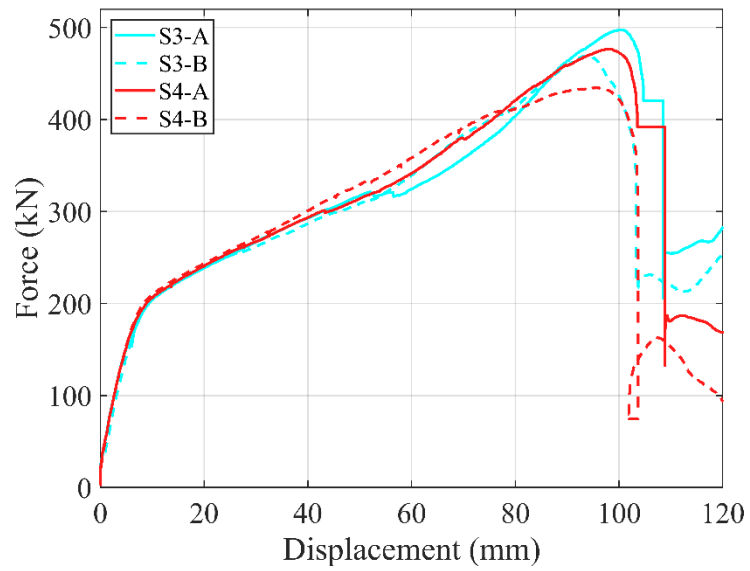
Fig. 14. Experimental failure of CHS fillet welded specimens (C0-A and C0-B).

Another important category is the PJP joint specimens, where the vertical cut in the bevel's root face was fabricated using two distinct methods: i) laser cutting, and ii) milling. The performance of RHS joints, examined in standard/special welding and RHS/CHS categories, is illustrated in Fig.

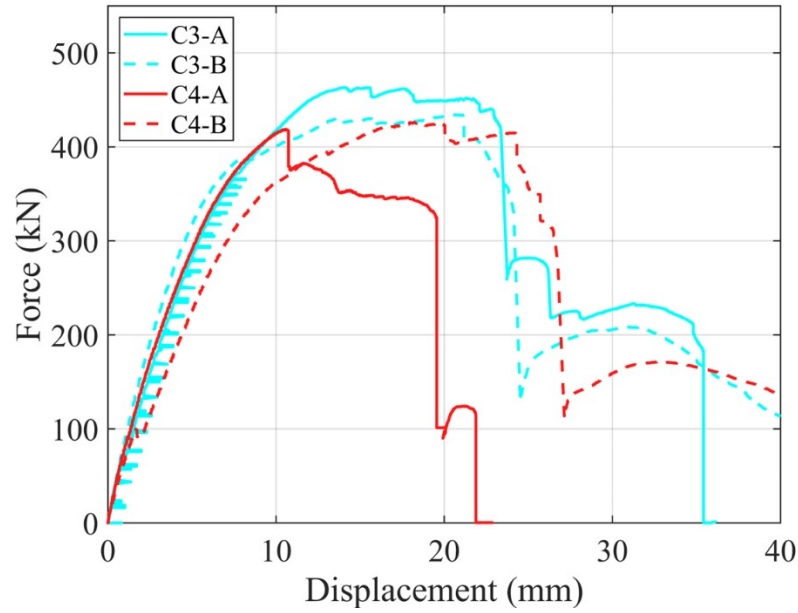
15.



(a) RHS standard welding type



(b) RHS special welding type

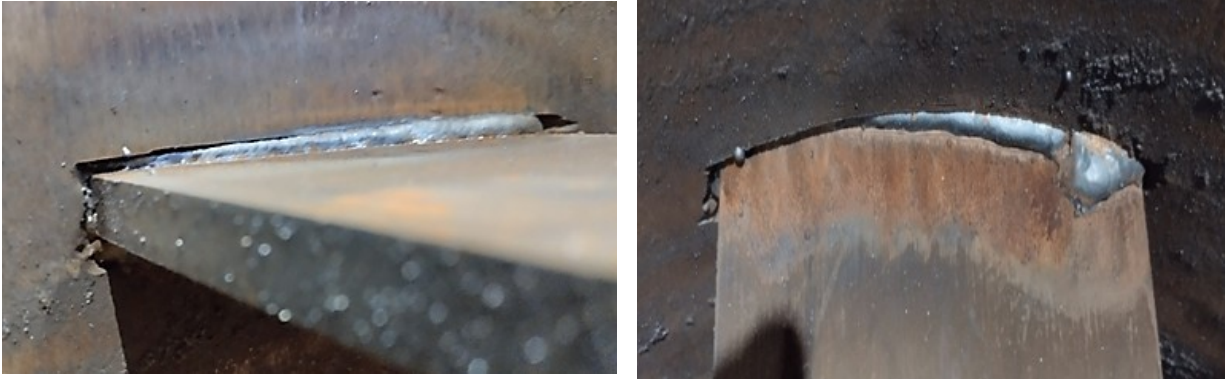


(c) CHS standard welding type

Fig. 15. Force - displacements diagrams of PJP specimens where the vertical cut is fabricated by dual laser cut (red curves) vs laser cut + milling (light blue curves).

As the results indicate, the improvement in average strength capacity (ΔV_u) variation for the laser + milling group relative to the dual laser-cut group is consistently positive, ranging from 2.85% to 8.13%. These findings suggest that the repeated localized heating at the root face caused by LCT combined with HAZ from the welding may degrade the quality of the joint and the fusion zone. The elastic behavior of the PJP specimens appears largely unaffected by the cutting processes. All in all, based on the testing of eight PJP specimens in this study, it is recommended to use laser cutting for the primary inclined cut and milling process for the secondary vertical cut. As shown in Fig. 15(c), the C4-A joint represents the worst-case specimen, where the use of dual laser cut considerably reduced the joint's quality and structural parameters including capacity, ductility, and post-peak stiffness reduction. From another perspective, one notable challenge in CHS joints is the use of penetration-type welding which poses difficulties for welders in achieving proper fusion and complete/partial penetration into the groove, due to the curved geometry of the column section.

As illustrated in Fig. 16, the curved geometry of CHS members presents a significant challenge in achieving uniform and consistent weld penetration. This inherent complexity also increases the costs associated with the weld quality checking procedures and verifying penetration depth. These challenges were mitigated in the case of PJP joints, where the root face facilitates more uniform weld penetration into the bevel. However, the achieved penetration remains suboptimal.



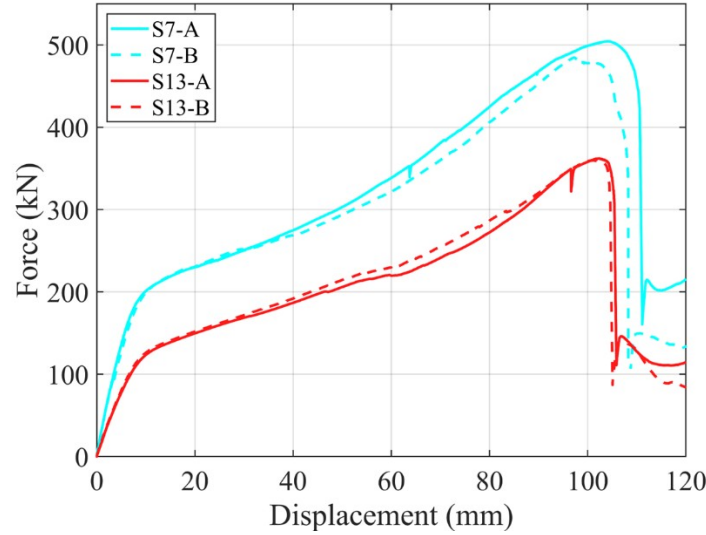
(a) Internal view of a CHS with PJP joint

(b) Internal view of a CHS with CJP joint

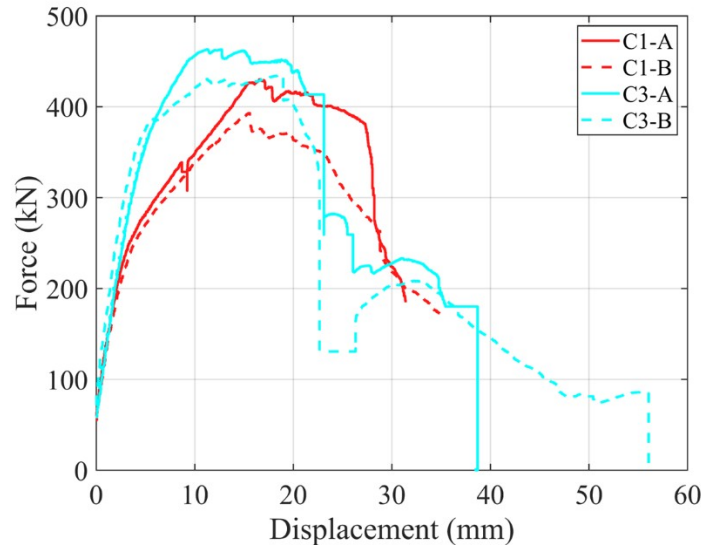
Fig. 16. Critical aspects of weld penetration in CHS joints.

To assess the effects of incorporating the root face in butt weld joints (PJP & CJP), Fig. 17 presents force-displacement curves of tested HSS butt weld specimens. Both specimen groups were prepared using the same standard welding type and grinding process. The PJP specimens were specifically selected from the laser plus milling cuts group, which demonstrated the highest performance among this joint category. It is important to note that the increased column thickness in the PJP specimens ($t_c = 12.5$ mm) compared to the CJP specimens ($t_c = 10$ mm) may also contribute indirectly to the overall capacity. Nonetheless, the penetration depth remains constant at 10 mm for both configurations. The most notable improvements are associated with the RHS PJP joints. These include an average increase of 75% in initial stiffness and 37% in ultimate strength, as depicted in Fig. 17(a). However, for CHS joints depicted in Fig. 17(b), the improvement is less pronounced and remains moderate. Only the average ultimate capacity experienced an 11.6%

improvement. This is also due to penetration limitations caused by the curved geometry that has already been discussed. Consequently, RHS sections are recommended for more effectively harnessing the potential of PJP welded joints.



(a) RHS joints

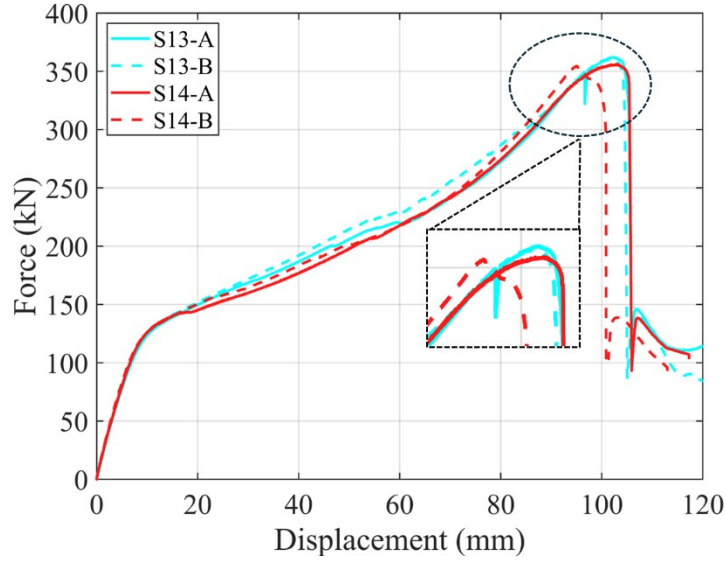


(a) CHS joints

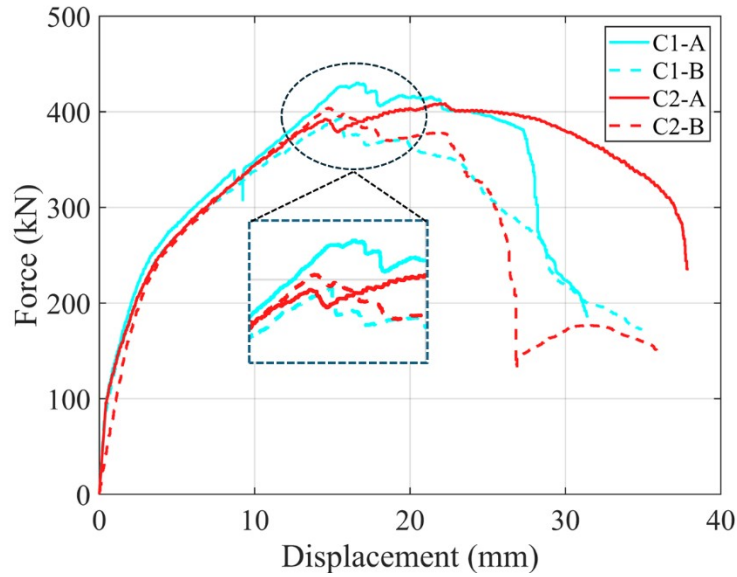
Fig. 17. Comparison between PJP joints with $t_c = 12.5$ mm and CJP joints with $t_c = 10$ mm.

The following sub-category examines the potential benefits of surface grinding prior to welding. It should be noted that this analysis is limited to four HSS-LCT-CJP tested specimens, as detailed in Table 3. Fig. 18 shows the influence of grinding on HSS-LCT-CJP joints appears

minimal. The results indicate no significant correlation between the grinding process and improved joint capacity. Consequently, omitting the grinding step for the laser-cut joints in this study may be advisable to enhance cost-effectiveness and reduce production time.



(a) RHS joints



(b) CHS joints

Fig. 18. Influence of grinding processes on the force-displacement behavior of HSS-LCT-CJP joints.

The final subcategory evaluates the potential advantages of the special welding procedure over the standard welding method. The key question to be addressed is whether this approach exhibits worthwhile enhancements in the joint's performance, considering the additional costs and time incurred. The special welding procedure has only been applied to RHS joints provided in Table 3. As the results indicate in Fig. 19, using the special welding procedure did not result in a reasonable improvement in the ultimate capacity. On the other hand, repeated cycles of heating and cooling within the fusion zone during multi-pass welding can degrade the joint quality.

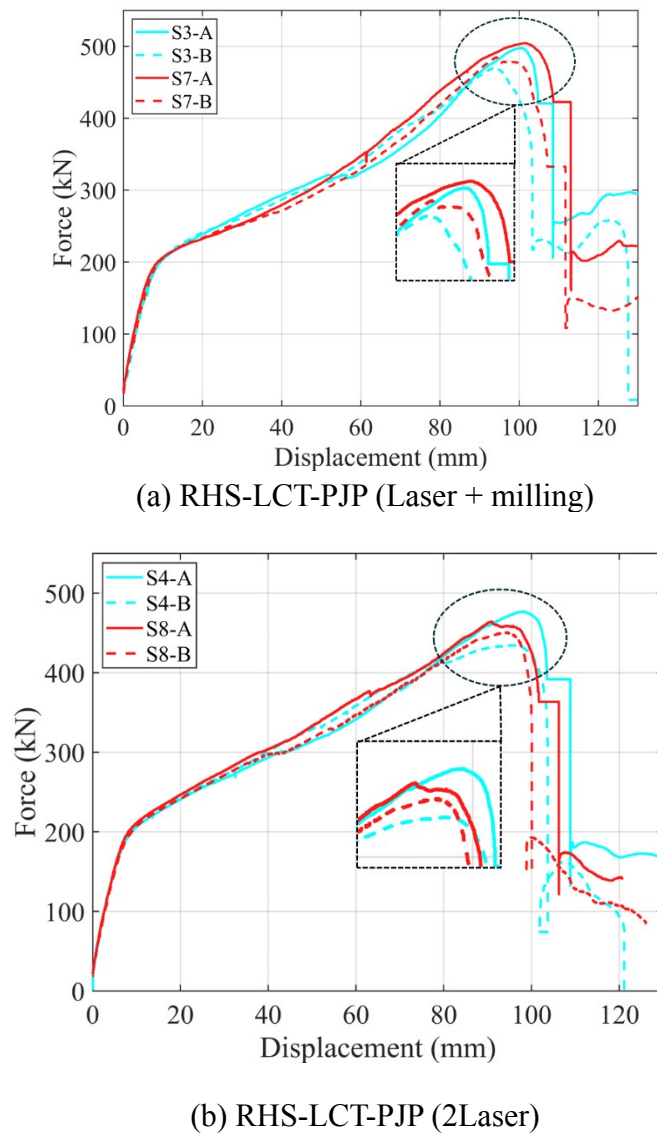


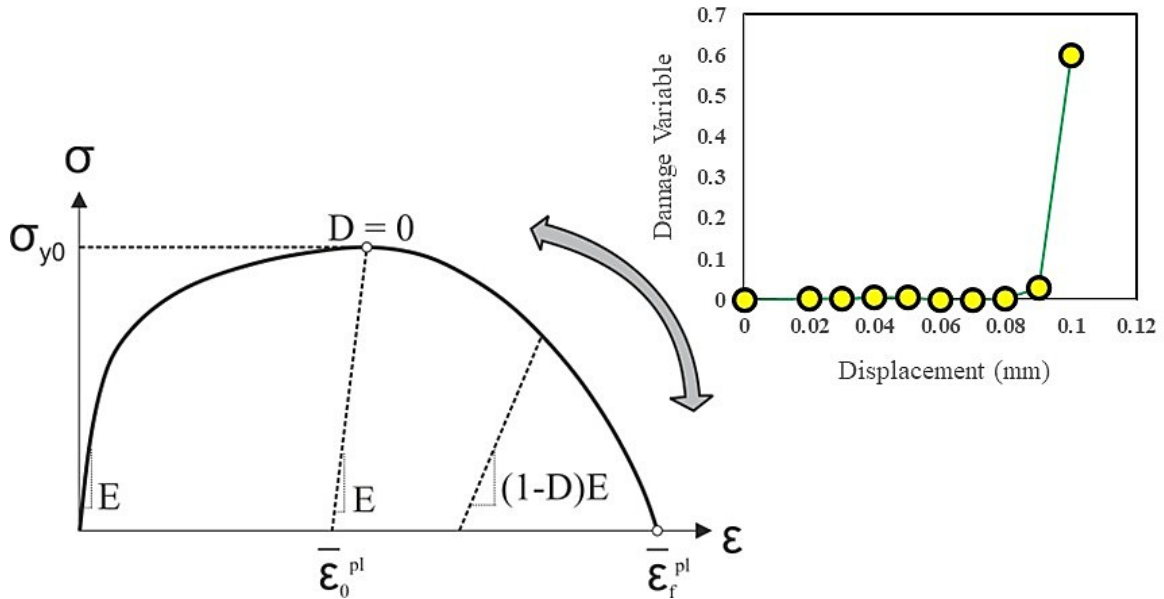
Fig. 19. Comparison of RHS-LCT-PJP joints using special vs standard welding methods.

3. FE numerical analyses

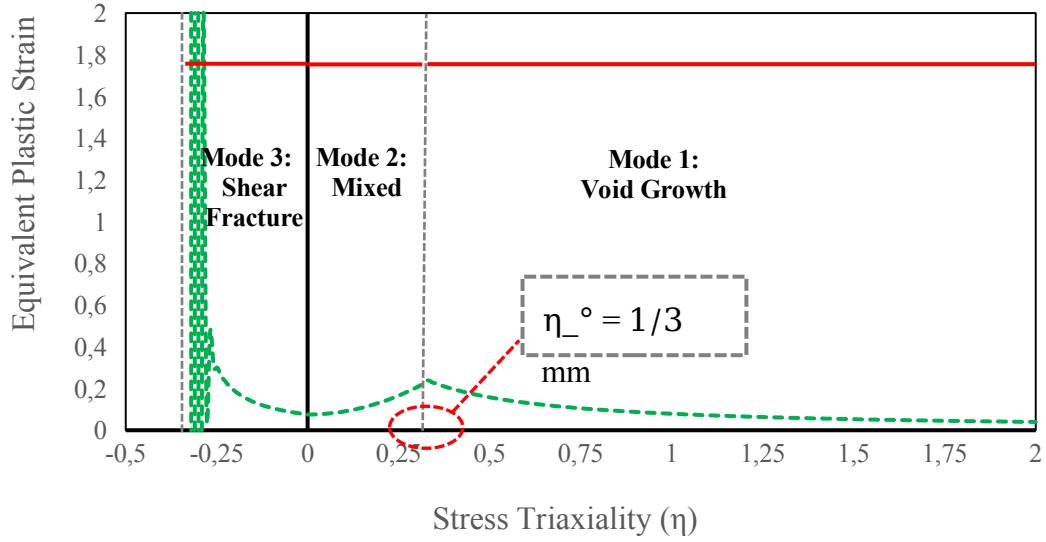
This section provides information on the FE modeling calibration and validation, which serves as the foundation for developing a surrogate model for conducting parametric analyses and assessing the capacity of RHS-LCT-FW connections.

3.1. Calibration and validation of damage criteria

Within the elastic range, the stress-strain behavior of steel material follows Hooke's law. Then, up to the ultimate strength, the steel material response is well represented by the Hollomon hardening law [29]. The materials' ductile damage modeling and constitutive parameters are developed with the calibration method proposed by Lee and Wierzbicki [30] which links the fracture locus model to material properties derived directly from uniaxial coupon tests. In this model, damage initiation occurs when the equivalent plastic strain-stress triaxiality relationship reaches defined threshold, as per Eq. (1), also depicted in Fig. 20.



(a) Damage evolution relationship and softening trend on the stress-strain curve



(b) The relationship between equivalent plastic strain and stress triaxiality at the fracture initiation moment

Fig. 20. Post-peak behavior of the materials illustrating the onset of damage and softening trend.

$$\bar{\epsilon}_o^{pl} = \begin{cases} \infty & \eta \leq -\frac{1}{3} \\ C_1 / (1 + 3\eta) - \frac{1}{3} & -\frac{1}{3} < \eta \leq 0 \\ C_1 + (C_2 - C_1)(\eta/\eta_o)^2 & 0 \leq \eta \leq \eta_o \\ C_2 \eta_o / \eta & \eta \geq \eta_o \end{cases} \quad (1)$$

$$C_2 = -\ln(1 - A_R) \quad (2)$$

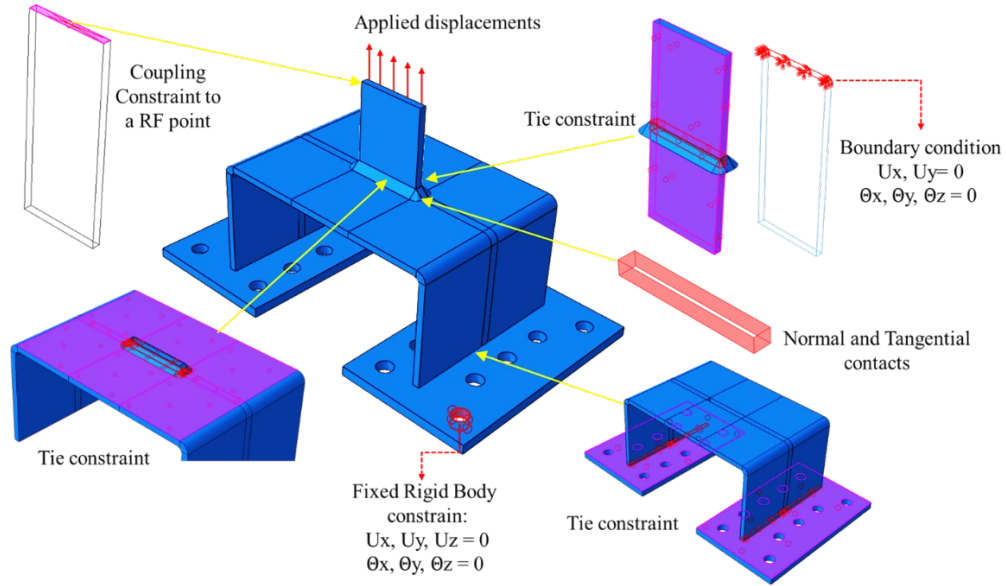
$$C_1 = C_2 \left(\frac{\sqrt{3}}{2} \right)^{1/n_o} \quad (3)$$

where $\bar{\epsilon}_o^{pl}$ denotes the equivalent plastic strain at the onset of fracture, C_1 represents this strain under pure shear conditions ($\eta=0$), and C_2 corresponds to its value under uniaxial tensile loading ($\eta=\eta_o \approx \frac{1}{3}$). The parameter A_R refers to the area reduction of the coupon gauge length. For all materials considered in this research, the corresponding fracture locus in Fig. 20(b) was derived and encoded into the simulation. The damage evolution phase in the FE non-linear simulation is a key stage that must be defined immediately after damage initiation. In the model, the steel

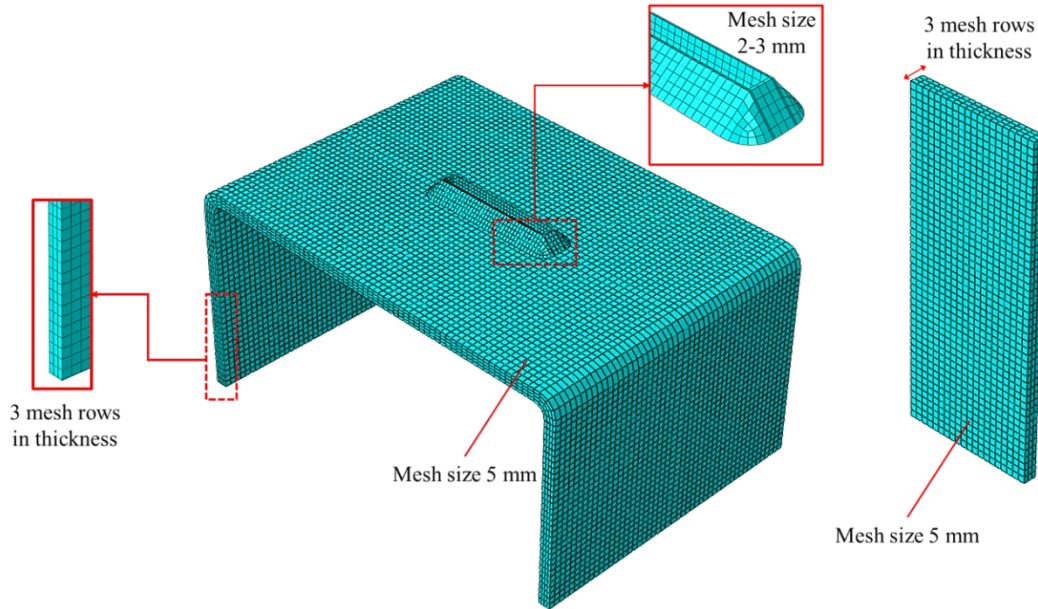
materials' post-necking behavior is governed by the relationship between the damage variable D and the nonlinear equivalent plastic displacement, $\bar{u}^{pl}$, as shown in Fig. 20(a). This relationship is calibrated from the softening branch of stress-strain coupon test curves.

3.2. Validation of FE Modeling for RHS-LCT-W Joints

This section outlines details of the FE modeling framework in Abaqus software to enable high-fidelity simulations of the HSS-LCT-W joints under monotonic tensile loading. Considering the monotonic nature of the test, isotropic hardening is the best choice for materials. As shown in Fig. 21(a), normal and tangential contact conditions were defined in the modeling to prevent surface penetration and to account for interface friction. Additionally, a fully restrained boundary condition was applied to the inner surface of bolt holes which represents the pretensioned bolted joint connection to the frame. The peripheral end region of the passing-through plate was constrained to permit only vertical displacement under the actuator grip. Tie constraints were applied at the welded interfaces, including the connection between the column and two end plates as well as the intermediate weld between the column and the passing through plate. The welding process produced an excessive weld reinforcement with an estimated throat thickness of approximately 4 mm, which is modeled as a weld layer positioned above the surface of the CJP welded models. A reference point coupled to the center of the passing-through plate was defined to control the displacement during the analysis and maintain compatibility with the test setup. Based on European Hollow Sections standard EN 10210-2:2006 [31], the external and internal corner fillet radii for rectangular square hollow section columns whose thickness is equal to t_c , are designated $1.5t_c$ and $1.0t_c$, respectively, in the modeling. A combination of mesh refinement and partitioning strategies was applied to facilitate the use of structured hexahedral C3D8R elements. This results in a highly ordered mesh configuration, as illustrated in Fig. 21(b).



(a) Boundary conditions, displacements, and constraints



(b) Mesh size and status in the FE components

Fig. 21. RHS-LCT-W joint FE model.

The mesh size was set to 2–3 mm in the critical regions of the welds and their surroundings, while a coarser mesh of 3–5 mm was set in the remaining areas. As demonstrated by the mesh pattern and sensitivity analysis in Fig. 21(b) and Fig. 22, this setting offers an optimal trade-off between computational efficiency and accuracy. Previous experimental and numerical studies[13,

27] have reported that using a relatively coarse mesh in simulations of HSS welded joints has a negligible influence on its pre-peak non-linear performance and initial stiffness. This is primarily because the analysis focuses on the onset of failure rather than tracking the propagation of micro-cracks through the mesh elements.

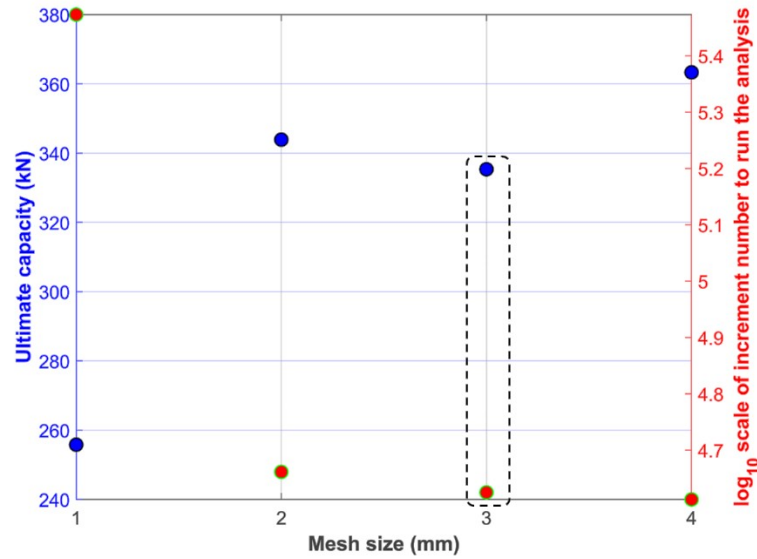
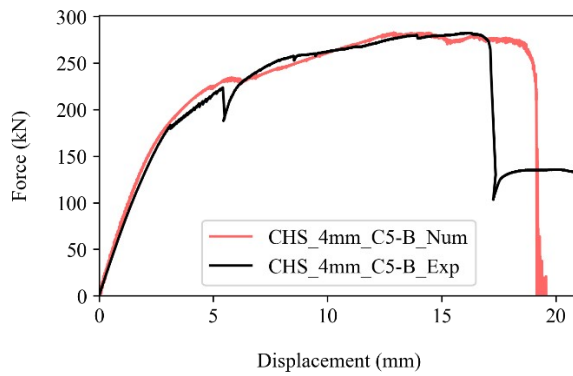


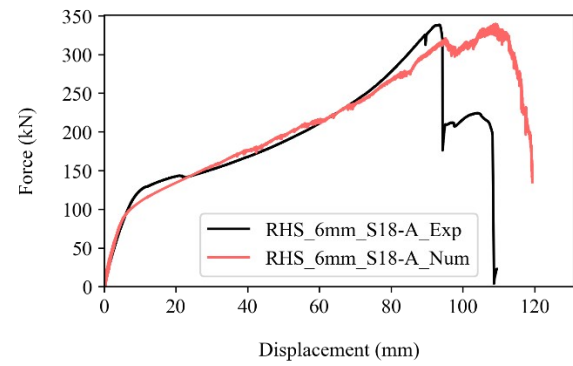
Fig. 22. Mesh sensitivity analysis on S18-A RHS-LCT-FW joint.

When two connected members in a FE model have incompatible mesh sizes or scales, it can lead to errors in force transfer, displacement continuity, or even solver convergence. Therefore, a fine mesh can lead to significant mesh refining in other elements resulting in a long-time analysis. As observed in Fig. 22, the 1 mm mesh size has a high ultimate capacity which is due to its sensitivity to ductile damage parameters calibration such as plastic failure displacement of individual elements. Therefore, in the absence of such refinement, discrepancies in the predicted ultimate strengths are unavoidable implying that each mesh element size requires a separate calibration of the material damage parameters. Furthermore, a minimum of three mesh layers through the thickness of each joint's component is advised to capture through-thickness instability phenomena. The validation focuses on the FE simulation of one RHS and one CHS joint for achieving

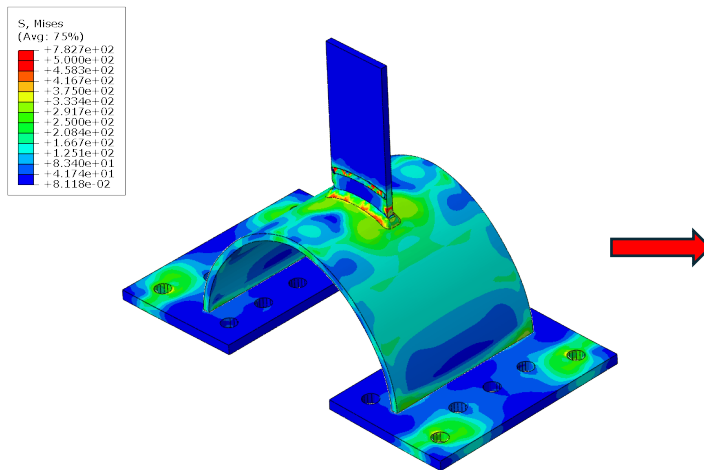
convergence in both force–displacement responses and plastic deformation characteristics. To this end, the S18-A RHS joint with a 6 mm weld throat thickness and the C5_B CHS joint with a 4 mm weld throat thickness were selected. As depicted in Fig. 23, the numerical models show a strong correlation with the experimental results to reproduce the force-deformation responses across the elastic, plastic, and failure stages. Additionally, Fig. 23(c) and Fig. 23(d) demonstrate that the fracture modes and the overall deformations of the HSS models are in close agreement with experimental specimens. These results affirm the model’s suitability for subsequent parametric analyses.



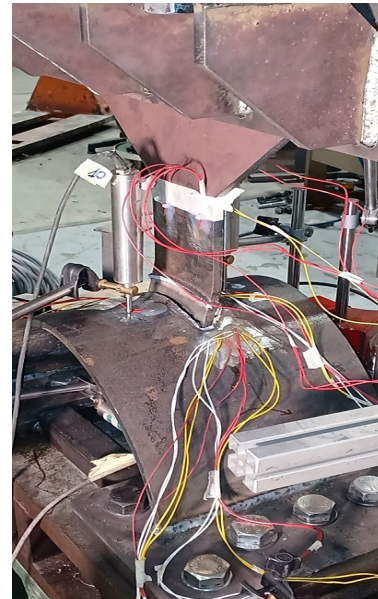
(a) C5_B CHS specimen

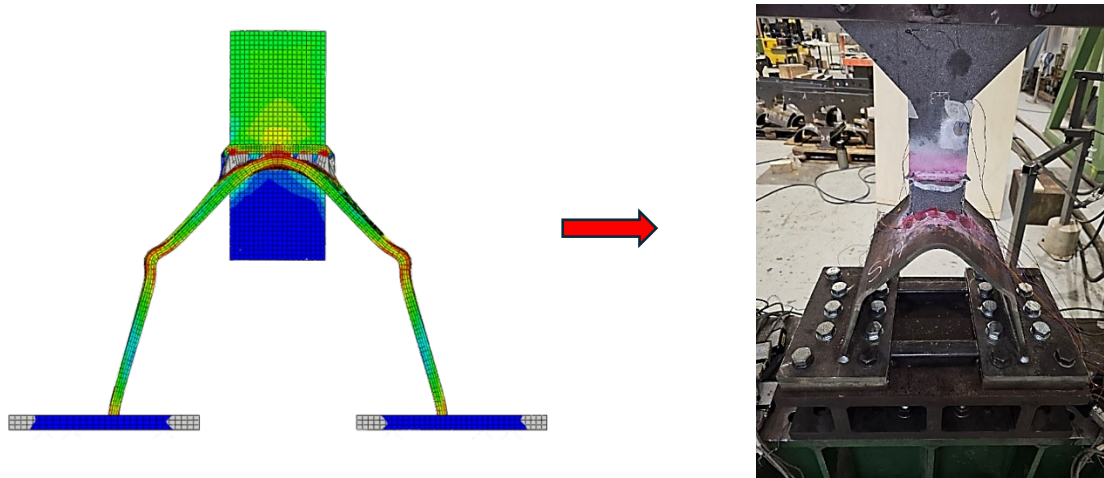


(b) S18_A RHS specimen



(c) C5_B CHS specimen





(d) S18_A RHS specimen

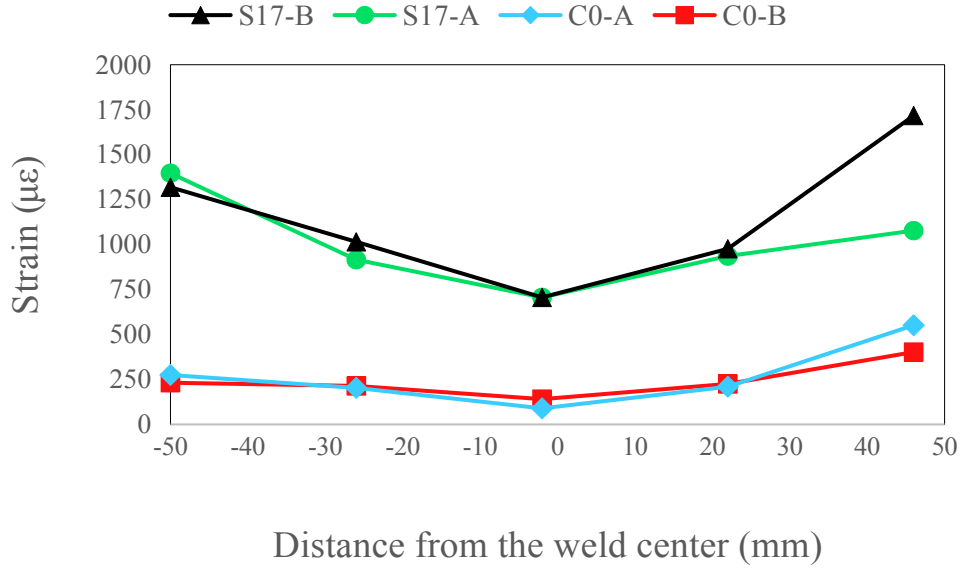
Fig. 23. FE model validation of the HSS joints comparing numerical and experimental results.

4. Surrogate modeling for capacity estimation of RHS-LCT-FW joints

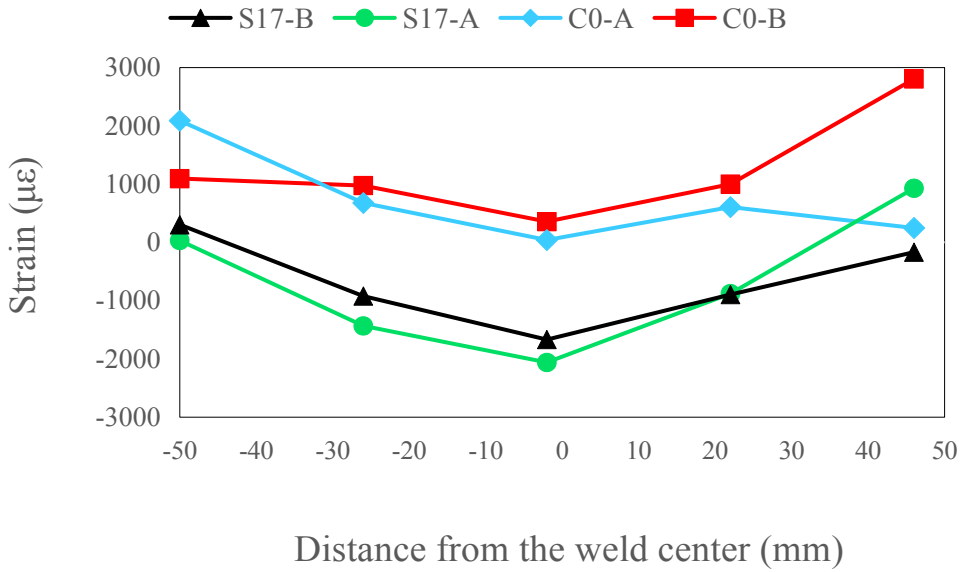
4.1. Stress distribution and design basis of HSS fillet welded joints

This section explores the theoretical framework underlying the capacity calculation of the primary-weld-fracture RHS-LCT-FW joints with a focus on the stress distribution mechanism. The ultimate goal is to develop new capacity equations for RHS fillet-welded joints, incorporating the effective weld length concept. The strength of the fillet-welded joints relies on the hollow section column stiffness and the connection members' geometry and relative flexibility [13, 17, 26]. As demonstrated in previous studies and supported by the initial phase of this research [13, 16], the stress distribution adjacent to plate-to-CHS fillet-welded joints is notably non-uniform. In detail, the stress and strain along the weld tend to exhibit a concave pattern, where the corner regions concentrate greater values compared to the mid-span owing to their rigidity. Experimental observations at 20% and 50% of the ultimate load, illustrated in Fig. 24, confirm the presence of undeniable inactive weld segments along both CHS and RHS joints, which are defined as segments that remain below their load-bearing potential when adjacent areas have already reached or

exceeded their ultimate capacity. This highlights the importance of accounting for the non-uniform stress distribution pattern in the design and assessment of HSS-LCT-FW joints.



(a) $0.2V_u$

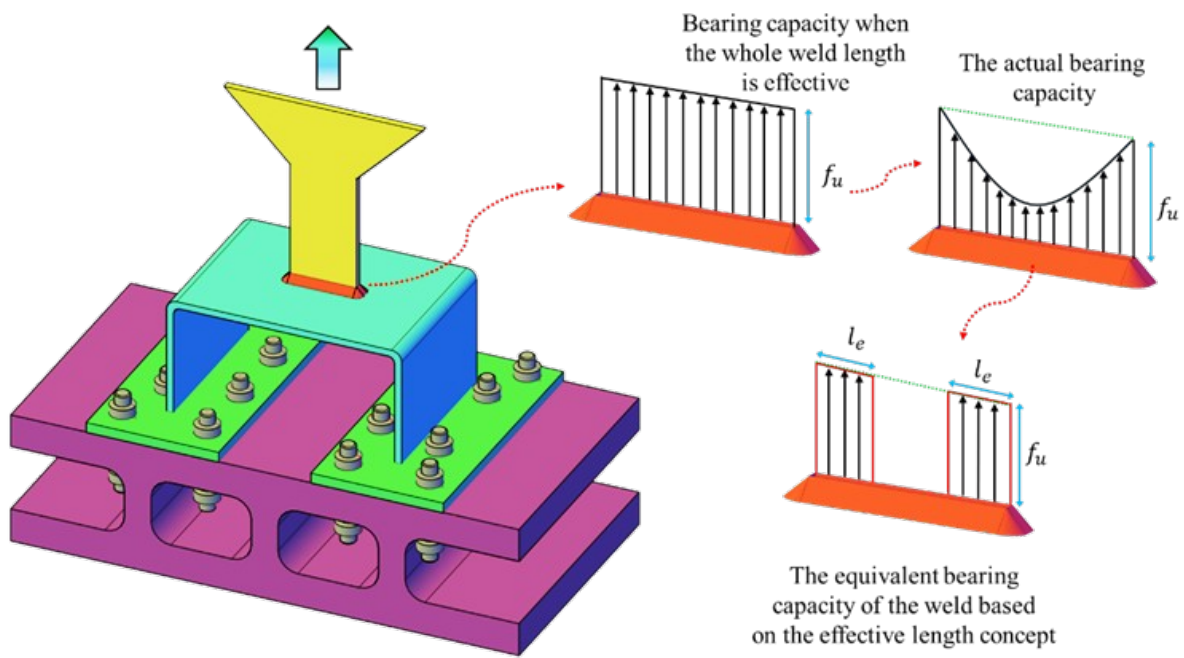


(c) $0.5V_u$

Fig. 24. Strain gauge data distribution over HSS welded joints at different ultimate strength steps.

Effective stress distribution, recognized by the design standards [15, 19], is a conceptual geometric approach for HSS fillet welded joints that identifies the portion of the weld actively

contributing to load bearing; however, the total stress distribution is uneven along the weld. Along the longitudinal length of an HSS fillet welded joint, some weld sections reach their ultimate capacity while others experience comparatively lower stress. To facilitate the assessment of the joint's capacity, an equivalent weld effective length consistent with the regions with the full capacity is considered, as shown in Fig. 25.



(a)

Fig. 25. Visualization of the weld effective length concept for the calculation of HSS fillet welded joints.

ISO 14346 [32] allows fillet welds in RHS section joints to be designed using one of two approaches: (i) ensuring the weld size develops the full capacity of the connected member, referred to as the “capacity method”, or (ii) designing the weld to resist the actual applied loads from the connected member, commonly referred to as the “fit-for-purpose” method. The capacity method is most suitable in scenarios where there is significant uncertainty in design forces, such as accidental loads or seismic actions. On the other hand, the fit-for-purpose method is acknowledged as an efficient approach that can lead to reduced weld sizes and associated costs. When utilizing this method, it is essential to account for the joint’s uneven stress distribution along the weld. EN 1993-1-8:2005, Section 7.3.1(6) [15] introduces a provision allowing for the use of smaller weld sizes provided that the resistance, deformation capacity, and rotational capacity are accurately accounted for in the design. The following sub-sections provide a detailed explanation of how to implement the effective weld length approach.

4.2. Evaluation of the effective weld length in HSS joints

This section begins with the Directional Method to determine the nominal design strength of fillet-welded joints, (R_n), introduced in EN 1993-1-8:2005 standard 4.5.3.2 [15]. The formulation typically is in terms of the ultimate tensile strength of the filler/base metal, the effective throat area of the weld, expressed as $A_w = t_w l_w$ or $t_w l_e$, in which t_w and l_w are the weld throat thickness and total length. It also includes the resistance reduction factor, ϕ_w , along with the effective weld length defined as a fraction of the total weld length ($l_e = \alpha' l_w$). According to Eq. (4) and Fig. 26, the load-carrying capacity of fillet welds is determined by resolving stress components on the theoretical throat plane. The fillet joint strength, applicable to both RHS and CHS configurations, is computed by key parameters such as the theoretical angle between the effective throat and fusion face, γ' , the angle between the direction of loading and the weld axis, θ , the ultimate strength of the

weaker component of the joint, f_u , and β_w which is a correlation coefficient with a standard value of 0.9 specified in Table 4.1 of EN 1993-1-8:2005 [15] for cold-formed or hot-rolled hollow sections with a nominal yield strength of 355 MPa. Finally, the partial safety factor $\gamma_{M2} = 1.25$ is applied, as recommended in [33].

$$\phi_w R_n = \frac{1}{\gamma_{M2}} \times \frac{f_u t_w l_e}{\beta_w} \quad (4)$$

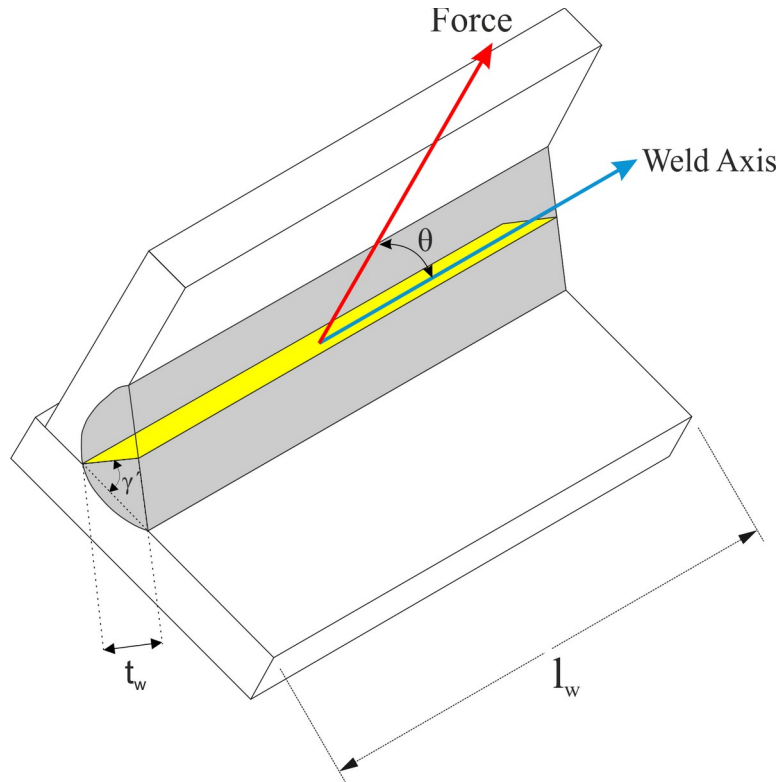


Fig. 26. Eurocode capacity equation parameters considering the plane of weld throat.

Eurocode [15] implicitly incorporates the effective width concept, which is conceptually similar to weld effective length, but the principle is used for failure modes such as punching shear of the connected member, as design equations indicated in EN 1993-1-8:2005, Table 7.13 [15]. This suggests that this standard fundamentally supports the weld effective length/width concepts; it

remains conservative and simplified in its current form for RHS welded joints and therefore necessitates further refinement to enhance its predictive accuracy and applicability. Eq. (5) has been provided in EN 1993-1-8:2005 Table 7.13 [15] and AISC Design Guide 24 [34]:

$$B_e = \left(\frac{10 t_c}{W_c} \right) \left(\frac{F_{y,c} t_c}{F_{y,s} t_s} \right) W_s \leq W_s \quad (5)$$

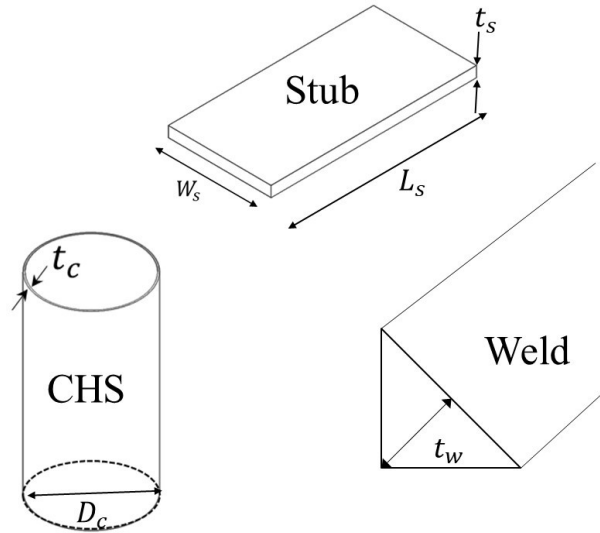
where B_e is the effective width of the plate or rectangular HSS branch. $F_{y,c}$ and $F_{y,s}$ are the yield stresses of the column and the passing-through plate, respectively. AISC Design Guide 24 [32] has a clearer viewpoint towards the weld effective length concept, which applies to both the weld and the connected member. In conclusion, the weld effective length is a crucial aspect of HSS-LCT-FW connection performance and design. The following sub-section is dedicated to deriving novel solutions for calculating the capacity of RSS-LCT-FW joints.

4.3. Surrogate modeling of design strength in RHS-LCT-FW joints

The objective of this sub-section is to develop a standardized procedure for assessing the capacity of RHS-LCT-FW joints in response to the limited availability of data in this field and the complex nature of the load transfer and failure behavior. This equation serves a dual purpose: i) it can be directly applied in designing RHS joints, or ii) integrated into the component method to calculate the joint's rotational stiffness. The first step involves generating a comprehensive and diverse dataset that sufficiently covers the entire response surface. Subsequently, an equation is formulated to fit this response surface obtained by FE analyses, ensuring that the final form is inclusive and practical. A total of 40 FE samples were generated based on the RHS validated model, to form a dataset complemented by experimental results from four RHS tested joints (S17-A to S18-B). It is important to note that all FE models have identical geometric, material, and boundary features; however, linear elastic material properties were assigned to both the column and the passing-through plate to only examine the weld failure mechanism. This combined dataset

of 44 samples can provide enough responses across a broad spectrum of non-dimensional parameters. As confirmed by prior research [14, 16, 17], the design capacity of HSS-LCT-FW joints is deeply influenced by the non-dimensional parameters $\beta = \frac{W_s}{D_c}$, $\gamma = \frac{D_c}{2t_c}$, and $\mu = \frac{t_w}{t_s}$, as dimensions shown in Fig. 27. Scalability analysis can assess how well a sub-assembly adapts to different scales while maintaining consistency in the structural responses. To understand if the mentioned non-dimensional parameters are sufficient to estimate the HSS welded joint's capacity, the validated CHS-LCT-FSW joint model is analyzed with varying diameters, as illustrated in Fig. 27(a), while keeping other geometric and material properties constant. These analyses were carried out with 10 different scales and are expected to yield a constant effective length parameter.

Number	dc
1	200.00
2	233.33
3	266.67
4	300.00
5	333.33
6	355.60
7	400.00
8	433.33
9	466.67
10	500.00



(a)

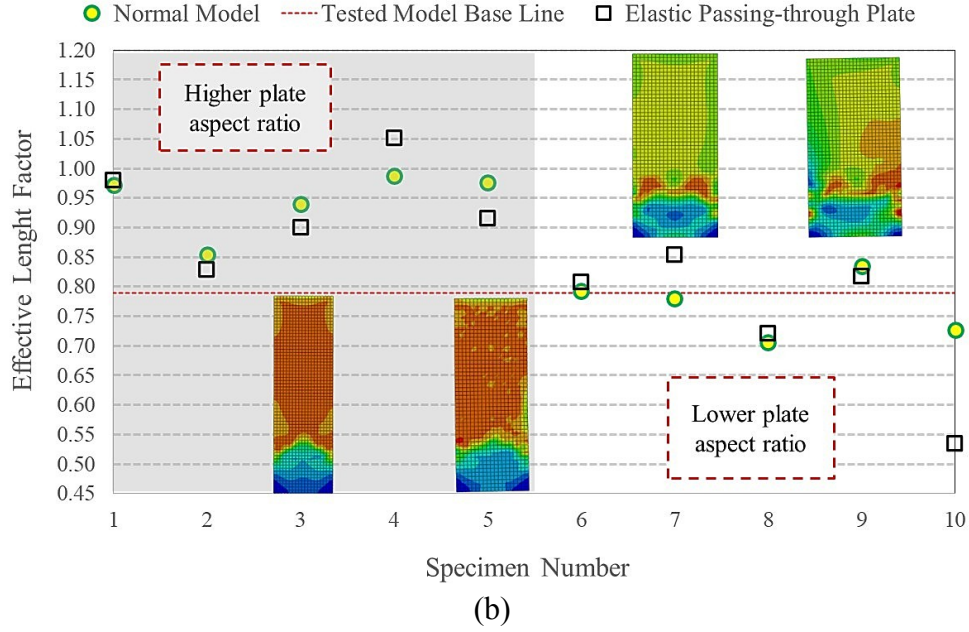


Fig. 27. Results of scalability analysis on the validated CHS-LCT-FW joint: (a) Overview of ten numerical models with varying outer diameters alongside showing dimensional parameters of the joint, and (b) Numerical results of the effective length parameter, l_e , in models with different diameters highlighting the influence of the plate's aspect ratio.

As shown in Fig. 27(b), when the plate's aspect ratio is high, the stress can more effectively influence the passing through plate. Consequently, it directly concentrates on the welded joint resulting in a more uniform stress distribution across the joint and a higher effective length. In contrast, when the aspect ratio is low, the loading struggles to stress the passing through plate leading to uneven stress distribution and a reduced capacity. This phenomenon introduces a new influential non-dimensional parameter, $\kappa = \frac{L_s}{W_s}$, which accounts for the aspect ratio of the passing-through plate. Just note that in the remainder of the study, the L_s parameter is considered from the column face, regardless of the penetration depth of the passing-through plate into the column.

After deriving the most influential non-dimensional parameters that affect the performance of HSS-LCT-FW joints, the ranges of validity given by the research literature, standards, and practical applications in the market for each parameter are provided. The ranges of validity for the parameters β , γ , μ , and κ according to AISC 360-16 [19], light- to medium-weight structural

market applicability and research findings in [3], are as $0.25 \leq \beta \leq 0.75$, $17 \leq \gamma \leq 35$, $0.4 \leq \mu \leq 1.0$, and $1 \leq \kappa \leq 5$.

When no prior information about the functional behavior of a structure is available, the goal is to develop models that can reliably predict the behavior across the entire design response region [35]. Generally, experiments are expensive and time-consuming. Although numerical simulation is a more cost-effective alternative, it can still require considerable computational effort and time compared to the surrogated closed-form analytical expressions. Therefore, the first step is to use an optimal space-filling algorithm to extract the maximum amount of information with a limited number of FE samples. There have been several space-filling algorithms, such as the Constrained Maximin method [35], integrated mean squared error (IMSE) [36], and Latin Hypercube method [37]. In this research, the Maximin design method [35] is employed for the 40 FE sampling. The previous algorithms are either computationally demanding due to the optimization step required or not sufficiently efficient for non-rectangular design spaces [35]. However, the new Maximin method is a pool-based algorithm that avoids direct optimization. Instead, it starts with a pool of data points, as shown in Fig. 28(a). The process begins by selecting the first data point. The algorithm then searches for the point with the maximum distance from this point. Next, the pool is divided into two groups based on the minimum distance to the two reference points. Within each group, the algorithm identifies the data point with the maximum distance from its respective reference point. This loop repeats until the required number of samples is obtained and located far away from each other, as demonstrated in Fig. 28(b).

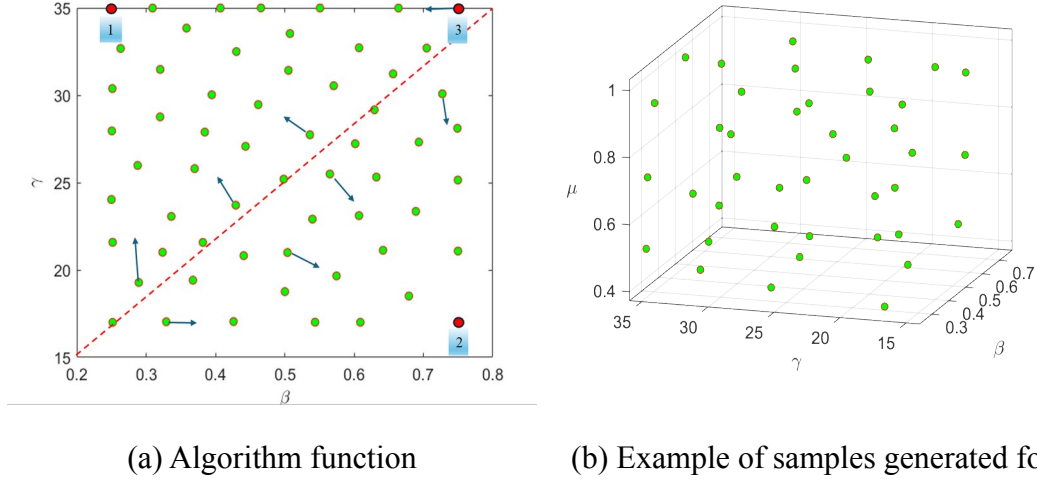


Fig. 28. Maximin algorithm for optimal sampling of RHS-LCT-FW FE models.

Table 4 and Table 5 present the forty FE samples of the RHS-LCT-FW joint type each characterized by different non-dimensional parameters β , γ , μ , and κ , and four experimental test results from joints S17-A to S18-B.

Table 4

Characteristics of RHS-LCT-FW joints sampled for the analytical assessment.

Number	D_c	t_c	t_s	L_s	W_s	t_w	Analysis Type
1	250.00	6.04	6.04	339.80	145.86	5.47	Numerical
2	350.00	5.01	5.01	433.17	88.01	2.04	Numerical
3	300.00	4.30	4.30	267.42	221.71	1.74	Numerical
4	250.00	5.33	5.33	925.21	185.49	2.14	Numerical
5	500.00	14.55	14.55	129.10	127.76	5.95	Numerical
6	300.00	4.30	4.30	86.86	80.87	3.17	Numerical
7	400.00	5.72	5.72	1465.28	293.89	5.25	Numerical
8	250.00	7.24	7.24	338.42	67.73	4.44	Numerical
9	500.00	8.03	8.03	575.23	126.04	7.98	Numerical
10	350.00	10.27	10.27	290.66	259.38	4.13	Numerical
11	260.00	3.74	3.74	206.21	193.99	3.70	Numerical
12	350.00	6.54	6.54	458.72	160.12	3.22	Numerical
13	400.00	11.68	11.68	108.01	101.83	11.58	Numerical
14	260.00	7.58	7.58	959.94	192.08	7.38	Numerical
15	260.00	3.73	3.73	780.45	156.74	1.90	Numerical
16	350.00	6.92	6.92	903.17	181.63	5.41	Numerical

17	250.00	6.99	6.99	300.00	77.16	6.97	Numerical
18	250.00	4.20	4.20	518.46	186.45	2.95	Numerical
19	500.00	7.22	7.22	668.95	241.94	6.75	Numerical
20	300.00	8.75	8.75	754.61	221.58	5.48	Numerical
21	500.00	9.87	9.87	316.59	125.91	7.76	Numerical
22	500.00	8.76	8.76	134.75	128.07	3.59	Numerical
23	260.00	4.75	4.75	109.14	107.38	4.73	Numerical
24	400.00	11.75	11.75	751.22	192.73	4.72	Numerical
25	450.00	13.01	13.01	235.82	224.62	8.16	Numerical
26	450.00	6.80	6.80	254.61	252.27	4.65	Numerical
27	400.00	5.78	5.78	356.53	102.85	3.98	Numerical
28	260.00	5.69	5.69	196.85	192.68	4.02	Numerical
29	250.00	4.68	4.68	679.22	182.09	4.67	Numerical
30	400.00	8.00	8.00	709.02	143.48	3.24	Numerical
31	350.00	7.11	7.11	681.46	253.07	2.85	Numerical
32	400.00	11.44	11.44	509.28	163.34	8.04	Numerical
33	300.00	4.29	4.29	670.97	136.42	3.39	Numerical
34	260.00	4.76	4.76	333.68	66.81	3.33	Numerical
35	500.00	12.11	12.11	381.73	125.45	5.39	Numerical
36	450.00	6.45	6.45	389.04	216.29	2.61	Numerical
37	450.00	9.05	9.05	259.54	250.93	3.67	Numerical
38	300.00	4.45	4.45	737.47	222.97	1.88	Numerical
39	450.00	7.86	7.86	1642.88	336.86	5.22	Numerical
40	300.00	5.77	5.77	431.47	126.46	5.73	Numerical
41	355.60	10.00	10.00	240.00	100.00	6.00	Experimental
42	355.60	10.00	10.00	240.00	100.00	6.00	Experimental
43	355.60	10.00	10.00	240.00	100.00	10.00	Experimental
44	355.60	10.00	10.00	240.00	100.00	10.00	Experimental

The outcome of numerical and experimental analyses on the joints are summarized in Table 5.

The effective length factor, $\alpha' = l_e / l_w$, assumed to be proportional to V_u / R_n (R_n from Eq. (4)), for the joints data.

Table 5

Comparison of the effective length factor estimations by two proposed methods.

Num	β	γ	μ	κ	$\frac{V_u}{R_n}$ (Eq. (4))	$\frac{l_e}{l_w}$ (Eq. (6))
1	0.58	20.71	0.91	2.33	0.29	0.25
2	0.25	34.95	0.41	4.92	0.57	0.42
3	0.74	34.92	0.40	1.21	0.30	0.20

4	0.74	23.45	0.40	4.99	0.14	0.20
5	0.26	17.19	0.41	1.01	0.38	0.52
6	0.27	34.85	0.74	1.07	0.37	0.38
7	0.73	34.98	0.92	4.99	0.27	0.20
8	0.27	17.26	0.61	5.00	0.53	0.51
9	0.25	31.15	0.99	4.56	0.38	0.33
10	0.74	17.04	0.40	1.12	0.25	0.24
11	0.75	34.79	0.99	1.06	0.14	0.20
12	0.46	26.77	0.49	2.86	0.16	0.16
13	0.25	17.12	0.99	1.06	0.50	0.53
14	0.74	17.14	0.97	5.00	0.24	0.25
15	0.60	34.89	0.51	4.98	0.12	0.12
16	0.52	25.30	0.78	4.97	0.20	0.16
17	0.31	17.89	1.00	3.89	0.52	0.47
18	0.75	29.75	0.70	2.78	0.13	0.15
19	0.48	34.62	0.93	2.76	0.11	0.13
20	0.74	17.14	0.63	3.41	0.29	0.25
21	0.25	25.32	0.79	2.51	0.25	0.36
22	0.26	28.54	0.41	1.05	0.28	0.32
23	0.41	27.35	1.00	1.02	0.27	0.17
24	0.48	17.03	0.40	3.90	0.32	0.36
25	0.50	17.29	0.63	1.05	0.27	0.35
26	0.56	33.11	0.68	1.01	0.11	0.08
27	0.26	34.60	0.69	3.47	0.25	0.39
28	0.74	22.84	0.71	1.02	0.25	0.21
29	0.73	26.69	1.00	3.73	0.15	0.16
30	0.36	25.01	0.40	4.94	0.23	0.26
31	0.72	24.62	0.40	2.69	0.18	0.18
32	0.41	17.49	0.70	3.12	0.34	0.40
33	0.45	35.00	0.79	4.92	0.14	0.16
34	0.26	27.29	0.70	4.99	0.38	0.32
35	0.25	20.65	0.45	3.04	0.34	0.46
36	0.48	34.90	0.40	1.80	0.07	0.14
37	0.56	24.85	0.41	1.03	0.15	0.16
38	0.74	33.69	0.42	3.31	0.10	0.18
39	0.75	28.62	0.66	4.88	0.14	0.16
40	0.42	26.00	0.99	3.41	0.22	0.19
41	0.28	17.78	0.60	2.40	0.67	0.49
42	0.28	17.78	0.60	2.40	0.69	0.49

43	0.28	17.78	1.00	2.40	0.47	0.49
44	0.28	17.78	1.00	2.40	0.46	0.49

To determine to what extent each non-dimensional parameter influences the output, a correlation analysis was carried out to clarify the interaction between the non-dimensional parameters and the weld effective length factor across the data. This helps to reduce the dimensionality in the final capacity equation. The Pearson correlation coefficient [38] is a statistical measure that quantifies the strength and direction of a linear relationship between two continuous variables. The Spearman rank correlation coefficient [39] is also a non-parametric measure that assesses the monotonic relationship between two variables. The values of these methods range from -1 to 1, where values close to 1 and -1 indicate strong positive and negative correlations, respectively. As presented in Table 6, the impact of κ and μ parameters on the weld effective length factor value, $\alpha' = l_e/l_w$, are minimal. However, the effect of the other parameters is prioritized in order of β and then γ .

Table 6
Pearson/Spearman correlation coefficients.

Pearson / Spearman	β	γ	μ	κ	$\frac{l_e}{l_w} = \frac{V_u}{Eq. (4)}$
β	1	0.18/ 0.11	-0.08/ -0.12	0.03/ 0.03	-0.64/ -0.65
γ	0.18/ 0.11	1	-0.03/ 0.04	0.1/ 0.1	-0.51/ -0.47
μ	-0.08/ -0.12	-0.03/ 0.04	1	0.05/ 0.01	0.12/ 0.15
κ	0.03/ 0.03	0.1/ 0.1	0.05/ 0.01	1	-0.02/ -0.04
$\frac{l_e}{l_w} = \frac{V_u}{Eq. (4)}$	-0.64/ -0.65	-0.51/ -0.47	0.12/ 0.15	-0.02/ -0.04	1

Given the complex and highly non-linear nature of the problem, it was decided to focus only on the two parameters, β and γ , which exhibit the strongest correlations with the outcome. This

approach enhances the practicality and ease of using the final capacity equation. The best fit to the data was obtained using a third-order polynomial surface, as defined in Eq. (6) and Table 7. This mathematical model effectively predicts the response of the data points, while achieving a low RMSE error of 7.4%.

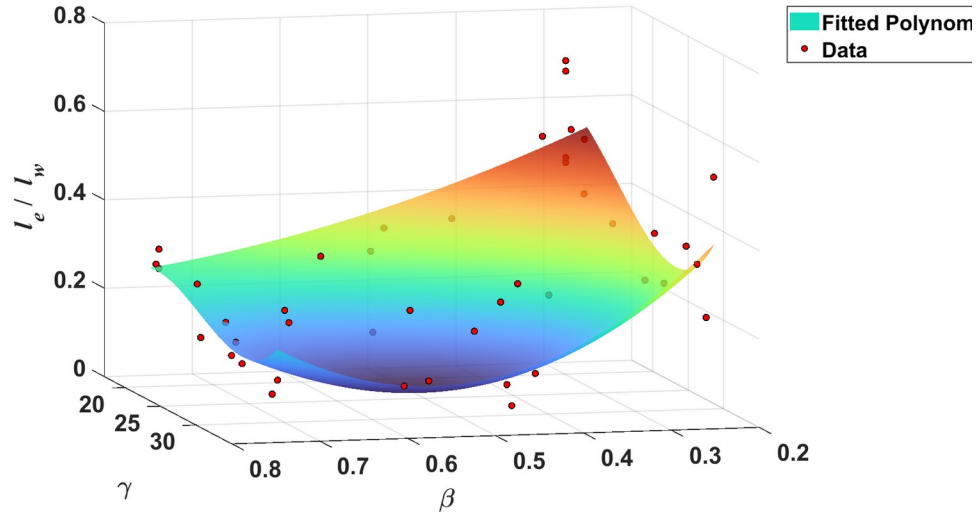
$$\dot{\iota}_{Eurocode, RHS} = (P_0 + P_1\beta + P_2\gamma + P_3\beta^2 + P_4\beta\gamma + P_5\gamma^2 + P_6\beta^2\gamma + P_7\beta\gamma^2 \dots + P_8\gamma^3)l_w \quad (6)$$

Table 7
Coefficients with 95% confidence bound for Eq. (6).

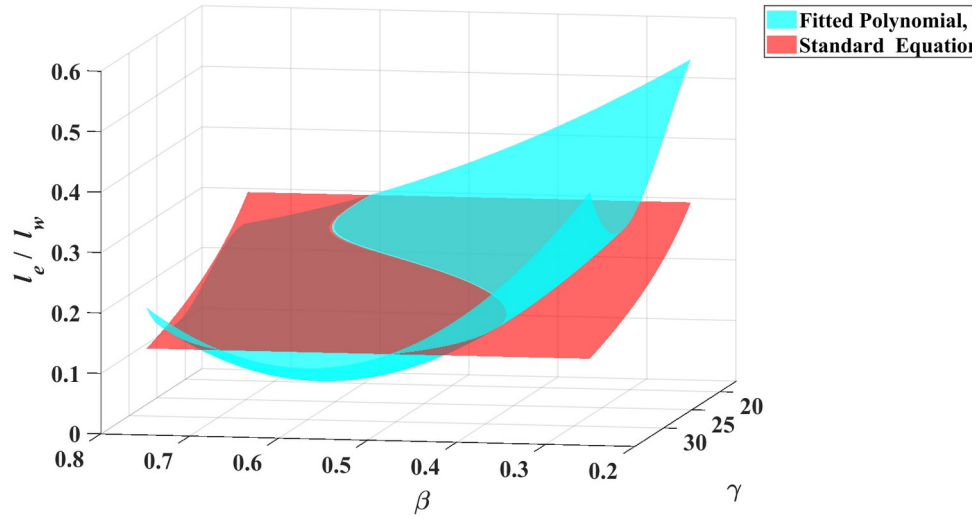
Coefficients (e-2)	P0	P1	P2	P3	P4	P5	P6	P7	P8
	4.951	-18.16	12.02	-169.4	-2.42	-0.637	13.3	-0.192	0.0108

The R-squared statistical measure in the regression model has been calculated for Eq. (6) as 75.8%, indicating that the model has strong explanatory power and a good fit, although some variability remains due to the complexity of the design space. Note that Eq. (6) must be incorporated into the Eq. (4). The performance of Eq. (6) response plane given the data and the comparison of this plane with the standard equation plane proposed in Eq. (5), which can be reformulated into the form of Eq. (7) for the similar material and thickness of the column and stub plate, is shown in Fig. 29.

$$\dot{\iota}_{Standard} = \left(\frac{5}{\gamma}\right)l_w \quad (7)$$



(a) Eq. (6) response surface factor against the data points obtained via $V_u / Eq. (4)$ ratio



(b) Comparing the effective length factor response planes of Eq. (6) vs Eq. (7)

Fig. 29. Performance of the weld effective length factor's response surfaces.

As shown in Table 5 and Fig. 29, lower values of the non-dimensional parameters β and γ correspond to an increase in the weld effective length. This trend suggests that a narrower passing-through plate width or a thicker column contributes to enhanced capacity of RHS fillet-welded joints. The range of the weld effective length parameter depicted in this figure pertains to RHS columns with medium thickness. As illustrated in Fig. 29(a), the response surface of Eq. (6)

demonstrates an appropriate fit to the data points. The newly derived equation surface shows a significant deviation from the simplified prediction by Eq. (7), while the most pronounced discrepancies are observed where both non-dimensional parameters have low values.

4.4. Reliability analysis

To investigate the safety margin of Eq. (6) given the available 44 data points, a reliability analysis as outlined in [3, 40, 41], is carried out using the following equations:

$$\phi_w = \phi_{\beta^{+i} m_R \exp(-\alpha \beta^{+i CV}) i} \quad (8)$$

$$\phi_{\beta^{+i}} = 0.0062 \beta^{+i} - 0.131 \beta^{+i+1.338 i} i \quad (9)$$

where $\phi_{\beta^{+i} i}$ is the resistance modification factor applied when $\beta^{+i} \neq 3.0$. m_R denotes the mean ratio of actual to predicted strength, and CV is its coefficient of variation. Based on [40, 41], the coefficient of separation $\alpha = 0.55$ and a target reliability index $\beta^{+i i} = 3.8$ is adopted in agreement with EN 1990 [42]. The reliability analysis using Eq. (6) over 44 data points, shown in Fig. 30, yields $\phi_w = 0.56$ which indicates a sufficient safety margin. Although increasing ϕ_w to 0.75 or 1 raises the failure risk, a value of 0.6 also remains acceptable with only minimal safety reduction.

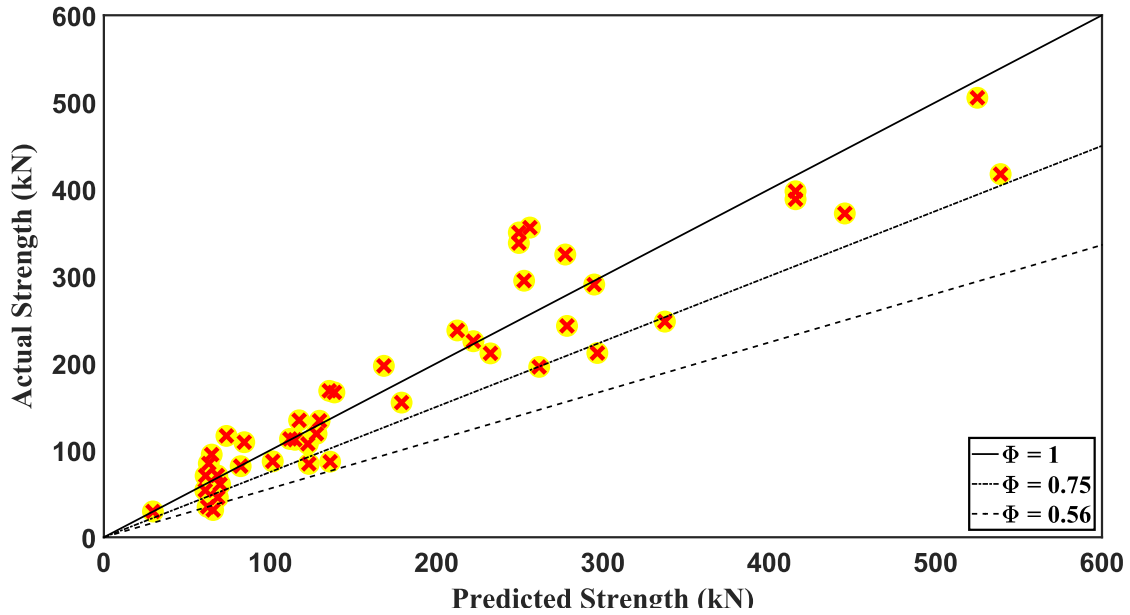


Fig. 30. Comparison between actual versus predicted nominal strength using the proposed effective length Eq. (6) which is integrated into the Eq. (4).

5. Conclusions

The primary objective of this research is to investigate recently proposed laser-cut passing-through welded joints applied to hollow sections to promote a robust, practical, and sustainable alternative. The study specifically examines the structural performance of CJP/PJP butt welded joints as well as full- and partial-strength fillet welded joints in this framework. Particular attention is also given to assessing the impact of weld effective length on the capacity of these hollow section connections. Given the nature of the problem, 35 experimental tests, 40 FE numerical analyses, and a set of analytical surrogating estimations have been cooperatively used to achieve the following findings:

- FSFW joint has been identified as the most efficient technique for hollow section joints in this research, outperforming CJP and PJP techniques in terms of strength, ductility, and stiffness based on experimental results. Notably, these tested specimens were the only ones in which the passing-through plate reached its ultimate capacity and failed before the weld fracture.

- PSFW joints in both CHS and RHS sections can be considered a reliable joint type for non-critical cases. It demonstrated the same ultimate strength values for both sections with a similar weld throat thickness and geometry. However, initial and secant stiffness were different. The comparison tips the balance in favour of CHS joints' stiffness.
- Generally, PJP joints are preferred over CJP joints with the same weld penetration depth, particularly for the use in RHS joints rather than CHS joints. The primary challenge in CHS sections is due to the difficulty of achieving proper welding penetration, as welders face obstacles in reaching full fusion due to the column's curvature. In view of the cut production, the results indicated a consistent improvement in the average strength capacity of RHS joints manufactured by the laser + milling process compared to the dual laser-cut group. The repeated localized heating at the root face caused by LCT cutting combined with HAZ from welding might degrade the quality of the fusion zone. Therefore, based on tests conducted on eight PJP specimens in the research, it is recommended to use laser cutting for the primary inclined cut and milling for the secondary vertical root-face cut.
- RHS joints displayed lower initial and secant stiffness compared to their CHS counterparts. This difference in stiffness is because of the distinct deformation mechanisms each section undergoes when subjected to tensile forces. The comparison tips the balance in favour of CHS joints' stiffness. Therefore, considering laser-cut technology has made the production of through plate/beam joints for HSS sections easy and robust, CHS sections can be suggested as appealing sections to augment the LCT joints' performance.
- Removing oxidation with a grinder and employing special welding procedures with multiple passes are unnecessary for HSS-LCT-W joints tested in this study. Eliminating these steps can

reduce costs and improve the project's overall sustainability. The reason might be smooth and consistent laser-cut edges with minimal roughness; however, it requires further investigation.

- A high-fidelity numerical model validated against experimental results showed that the vertical weldments are fully effective compared to horizontal ones, and the relevant HSS-LCT-W joint is under a uniform stress condition.
- The weld effective length concept for HSS fillet-welded joints is governed by four non-dimensional parameters: γ , β , μ , and κ . In this study, κ is introduced as a parameter representing the aspect ratio of the passing-through plate. For RHS joints, the γ and β parameters are sufficient for determining the capacity equation, as verified by the correlation analysis. By integrating four experimental RHS fillet welded joints results with 40 numerical simulations, which were strategically sampled using the Maximin space coverage algorithm and given the ranges of validity for each parameter, an equation was derived from a surrogated third-order polynomial plane. This equation provides a robust solution for predicting the capacity of the RHS fillet welded joint based on the weld effective length concept in the context of Eurocode 1993-1-8:2005 [15]. The reliability analysis is also conducted to support a safe estimation by the proposed equation.
- The main design consideration for HSS welded joints is that their capacity is positively influenced by a thick column and a narrower passing-through plate.

Credit authorship contribution statement

Shervin Safaieafageh: Formal analysis, Data curation, Investigation, Writing, Review & Editing.

Gabriele Zanon: Supervision, Data curation, Writing, Review & Editing.

Oreste S. Bursi: Supervision, Writing, Review & Editing.

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