GRANT journal
ISSN 1805-062X, 1805-0638 (online), ETTN 072-11-00002-09-4

Vol. 8, Issue 1

EUROPEAN GRANT PROJECTS | RESULTS | RESEARCH & DEVELOPMENT | SCIENCE

Full-scale experimental study of welded RHS T-joints with offset and it main outcomes

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Grant: SGS18/117/OHK1/2T/11
Název grantu: Welded Hollow Section Joints
Oborové zaměření: JN - Civil Engineering

Abstract The paper introduces brief outcomes of experimental and numerical studies of the mechanical resistance of welded T-joints composed from rectangular hollow section (RHS) components with certain offset of a brace relative to a centreline of a chord. Program of experimental research includes full spectrum of possible types of the members' offsets with only one type of the component set - 150x100x4mm for RHS-section used for chords and 50x30x4mm for RHS-section used for brace elements. Results of the T-joints experimental research, together with coupon tests of steel strips which were cut out from the profiles used in the specimens producing, are presented and discussed in detail. Finite element models created from brick finite elements using ABAQUS CAE was developed with the aim of calibration of the numerical models and experimental specimens in frames of presented study. Brief comparative analysis of load-displacement curves obtained in the tests and throughout of numerical analysis demonstrates sufficient convergence that will be used under preparation of program for the future parametrical research.

Key words rectangular hollow section (RHS), offset T-joints, steel structures, connections, stress-strain behaviour, numerical modelling

1. INTRODUCTION

In the most commonly used design rules for steel joints, such as Recommendations [1] developed by the International Institute of Welding, there are direct instructions designed to the calculations and design of the joints between HSS members. They require to coincide axes of chord and brace elements and saying nothing about joints with offset from the chord centreline. Nevertheless, the application of the eccentrically welded joints is on high demand. Such type of joints is able to provide a common enveloping surface both for the structural members and facade or finishing surfaces. Other type of the eccentricity in connections belong to the end panels of bridge or roof trusses where end brace member, as a rule oriented vertically, is attached directly to the tip end of the chord.

Two types of the welded RHS T-shaped joints (T-joints) with offsets schematically depicted in Table 1 are examined herein. The aim of the current paper is to present results of laboratory testing of mechanical behaviour of the offset T-joints under monotonically increased load and their using in verification of numerical models developed specially for the future parametrical studies with purpose of development of the guidance of their design. The specific connection geometry is described by connection members' dimensions (chord width, b_0, branch width, b_1, etc.), however, the geometry is typically presented using non-dimensional parameters (β, μ_0, μ_1, γ) that can be easily compared regardless of connection scale. The research program presented in frames of current study includes an experimental testing of the full-scale offset T-joints with β=0.3, μ_0=25.0, μ_1=7.5, γ=12.5 which lie in the border limits or out of scopes provided by [1]. These structural particularities of testing specimens are caused by the necessity to cover as much as possible spectrum of the joints' geometry.

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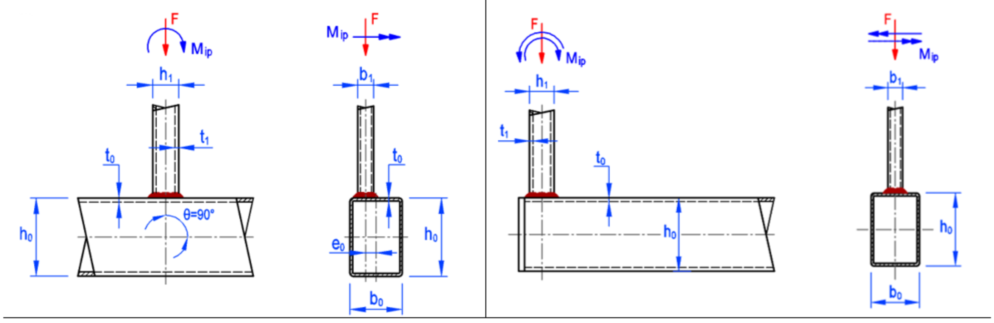
Table 1: Examined connection groups

Group 1. Offset from the chord centreline	Group 2. Offset toward the end



Geometrical parameters:

$\beta = b_1/b_0$ - width-to-width ratio;
$\mu_0 = b_0/t_0$ - chord width-to-thickness ratio;
$\gamma = b_0/2t_0$ - chord width-to-double-thickness ratio;
$\mu_1 = b_1/t_1$ - brace width-to-thickness ratio

2. EXPERIMENTAL STUDY

2.1 Program and methodology of testing

Nine specimens were designed for full-scale experimental study of its general mechanical resistance, deformation capacity and stiffness. While testing, the vertical displacement and local strains were measured. Predicted failure modes appeared and visually observed.

E4303 with nominal 0.2% proof stress, tensile strength, and elongation of 378 MPa, 421 MPa, and 32 %, respectively, were used for welding low carbon steel (S235 and S355) specimens. Such strict requirements to welding and to the thickness of the brace member were dictated by guarantee that failure of specimens occurred in the chord members rather than in the welds and brace.

All specimens were built on the special setup composed of supporting frame and bearing platform as shown on Fig.1. During the experimental tests of specimens to be compressed, the bottom

Table 2: Test Programme

Code of specimen	Quantity	Type of specimen	Steel grade			Applied force
			Brace	Chord		
			S355 J2H	S235 JRH	S355 J2H	
1.01.T.Ec.Co.235	1	Centreline offset	+	+		Axial force
1.02.T.Ec.Co.355	1	Centreline offset	+		+	Axial force
1.03.T.Ec.Be.235	1	Centreline offset	+	+		In-plane moment
1.04.T.Ec.Be.355	1	Centreline offset	+		+	In-plane moment
2.01.E.Sy.Co.235	1	Offset toward the end	+	+		Axial force
2.02.E.Sy.Co.235	1	Without offset	+	+		Axial force
2.03.E.Sy.Be.235	1	Offset toward the end	+	+		In-plane moment (in)
2.04.E.Sy.Be.235	1	Without offset	+		+	In-plane moment
2.05.E.Sy.Be.235	1	Offset toward the end	+	+		In-plane moment (out)

Abbreviation of 1.01.T.Ec.Co.235 can be decoded as follows:
1. a number of a joint,
01. an index number of a specimen
T.Ec. a type of a joint, viz, T-Eccentric or Centreline offset; E.Sy means Edge-symmetric
Co. a type of the load, viz, Compression; Be means Bending
235 a steel grade, viz, S235 JRH; 355 means S355 J2H

Each specimen composed by cold-formed rectangular hollow sections EN 10219-2, namely, 150 x 100 x 4 mm RHS member as a chord and 50 x 30 x 4 mm RHS member as a brace. Testing conditions were axial force applied on the brace centreline and in-plane bending moment applied on a brace top. The specimens were divided into two test groups, as it is shown on Table 1, the program of experimental study and labelling of specimens set out in Table 2.

The welds connecting brace and chord members were designed according to the EN 1011-1:1998 and were laid using shielded metal arc welding. The weld sizes in the test specimens are all greater than the larger value of 1.5t and 4 mm. The 4.0 mm electrodes of type

surface of RHS steel chord was in close contact with the bearing platform and an axial compressive load was applied at the tip of the brace. Close contact with the platform was provided by two specially designated plates at the ends of the specimen's chord fixed to the platform by screw clamps. T-joint specimens designed for bending loading were fixed to a column of the supporting frame and a lateral force which provides bending state was applied as it is shown in Fig.1b. There, support frames were connected to the strong floor firmly by anchor bolts. The 1000 kN capacity hydraulic jack was used to apply the axial compression and lateral force to the brace members of test specimens and monitored by the load cell, which was positioned concentrically between the hydraulic jack and the reaction frame.

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a) Gpoup 1. Offset from the chord centreline
b) Group 2. Offset towards an open-ended chord

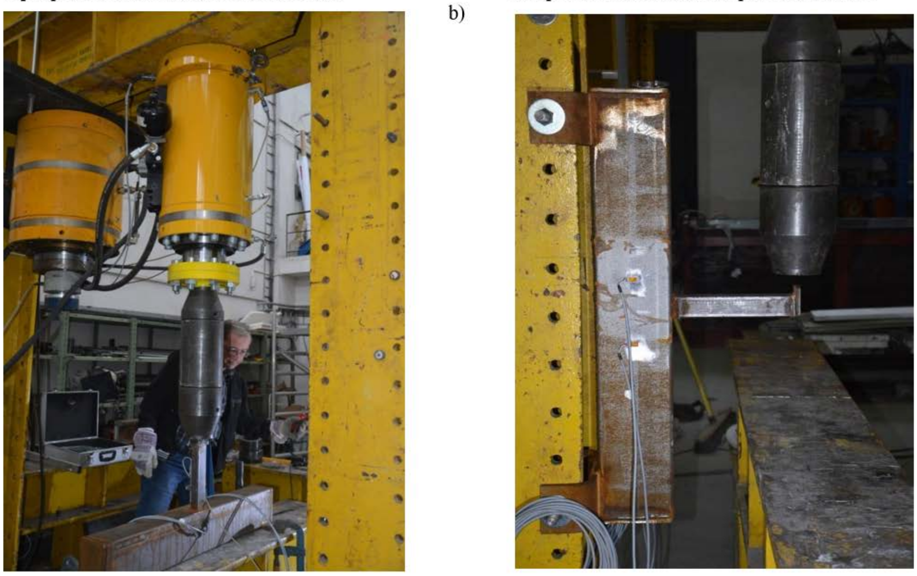


Fig.1. Test setup of the T-joint specimens

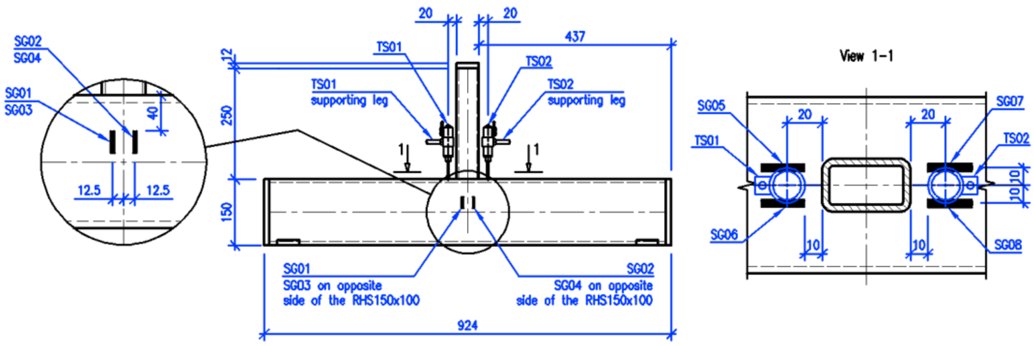


Fig.2. Arrangement of displacements gauges

Measurement plan of displacement and strain gauges is presented in Fig.2 for specimen 2.02.T.Sy.Co.235 as most illustrative case for the whole test series. Two displacement gauges TS01 and TS02 were arranged on the independent supports for measuring of main displacements of the chord face at the punching area. Eight strain gauges were additionally introduced for the evaluation of local displacements. Four strain gauges named SG01–SG04 corresponding to direction of the highest web deformations were placed on the opposite faces of the chord webs parallel to the axis line, and four strain gauges named SG05–SG06 corresponding to direction of maximal flange strains were placed at the top surface of the chord flange. A data acquisition system was used to record the load and strain at regular intervals during the tests.

Tests were conducted with variable rate of loading. Loading program for all specimens consisted of four parts. On the initial stages of the tests – from unloaded state to the level of (0.3-0.35)·P_{ult} - the rate of loading was characterized by higher values of

Fig.3. Coupon tests specimens and scheme of loading

0.25 mm/min. With increase of specimens' deformations, the rate of loading came down up to 0.1 mm/min with step of reduction of 0.5mm/min.

2.2 Coupon tests

Tensile coupon tests were performed in order to provide real material properties to an advanced FE model. The coupons were cut from specimens' material (additional pieces made from the same material) and tested in the rolling direction. A total of 8 tensile tests were conducted: 3 on steel S235 JRH and 3 on S355 J2H material taken from chord elements, and 2 on S355 J2H taken from brace elements. All coupons were cut from the middle plane of the profile facets to avoid hardening affected zones in corners. Material properties including Young's modulus E, the ultimate tensile stress σ_u and the corresponding strain ε_u, were recorded.

All tested coupons had a nominal thickness of 4 mm and a nominal width of 18 mm in the necked region. Fig.4 shows a typical coupon before and after testing. The tensile tests were conducted under strain control. The strain rates were defined in accordance with ISO 6892-1: 0.1 mm/min for the initial part of the tests, up to approximately 1% strain increasing to 2.2 mm/min thereafter.

MTS extensometers with two contact points were used to measure a longitudinal strength. It was installed directly onto the coupons under testing. A measured stress-strain curves for every specimen are shown in Fig.3.

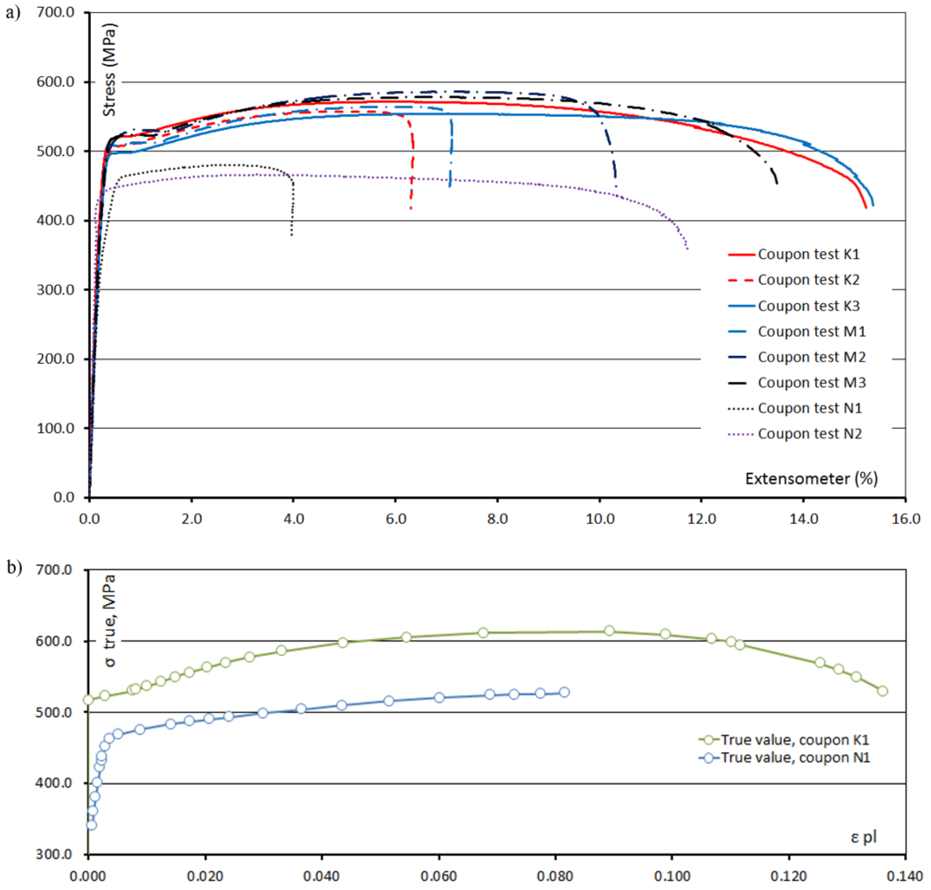
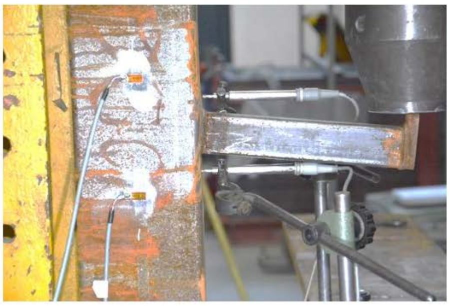


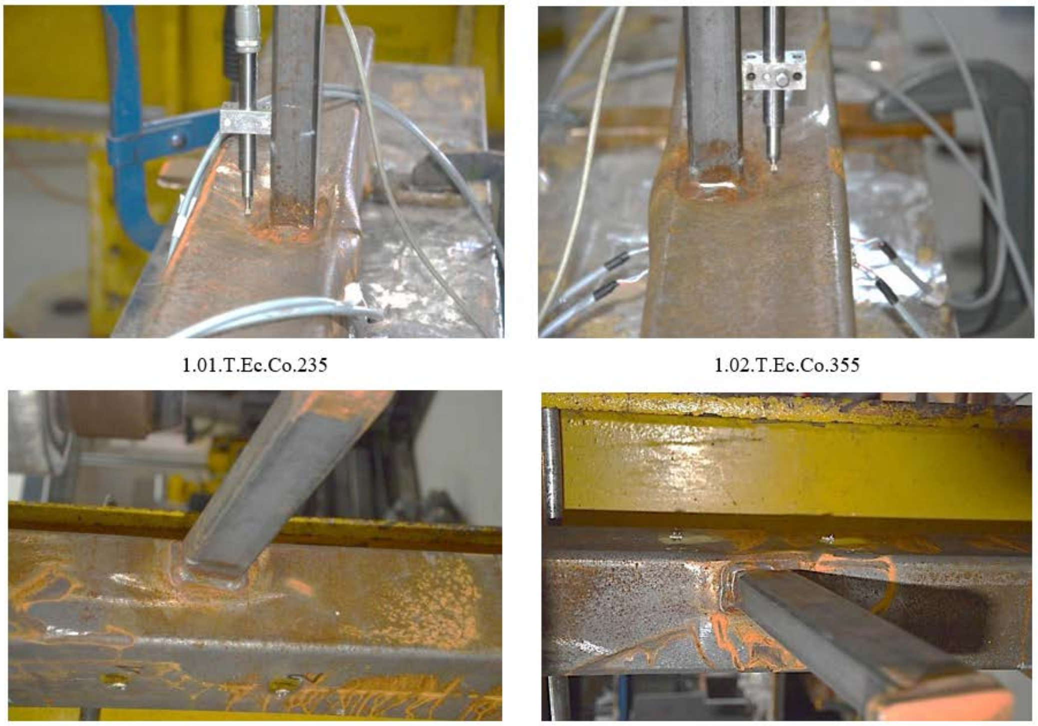
Fig 4. Stress-strain curves: a) – measured stress-strain curves, b) – true strength-strain curves

2.02.T.Sy.Co.235



2.04.T.Sy.Be.235

Fig.5. Modes of failure of joints without offset



1.01.T.Ec.Co.235 1.02.T.Ec.Co.355

1.03.T.Ec.Be.235 1.04.T.Ec.Be.355

Fig.6. Failure modes of specimens of Group 1.

2.3 Tests results and discussion

During the vertical and lateral loading process, joints were destroyed after elastic and large plastic deformations. The deformations were quite small in the initial elastic stage. With the increase of load, the RHS brace member remained almost undeformed due to the relatively high stiffness comparing with the RHS chord member. Chord flange and webs yielded gradually depending on loading scheme and specimens' type. Failure modes of the specimens without offset (2.02.T.Sy.Co.235 and 2.04.T.Sy.Be.235) are presented in Fig.5 and characterized by initial yielding of the flange in joining area with subsequent gradual involvement of adjusted zones of the chord webs in the process of plastification. Plastification of the chord webs began after the flange yielding for both types of specimens.

Patterns of failure for the Group 1 specimens demonstrated simultaneous local buckling of the web under the brace and yielding of the flange. For the specimens subjected to the moment action cracks failure occurred at the end-lap weld located in the tension zone of the brace as it is shown in Fig.6. Local buckling occurred at the top third of the chord web and differences in the failure modes for the chord produced from steels with different grades were not observed.

3. NUMERICAL MODELLING

The general-purpose finite element programme ABAQUS (CVUT University license) was used for the nonlinear numerical analysis of the all types of the specimens to validate tests outcomes and verify FE models. Both material and geometric nonlinearities have been considered. The modelling of the materials, weld, the inter action between chord and supports, load plate and brace as well as brace with chord through weld loading and boundary conditions were all considered in the finite element analysis. The FE models were developed based on the centrelines of the standard dimensions of the cross-sections. Mechanical properties of materials, which were described by their elastic and plastic behaviour, corresponded to the results of the coupon tests presented above. True stress-strain diagram (also presented on Fig.4) developed according to [2] was adopted as a basis for the mechanical properties' description.

Three-dimensional eight-node solid element with additional variables relating to the incompatible modes (C3D8I) was used in this study to model the components of the offset T-joints. The welding seams were considered in the finite element models due to its significant effect on the behaviour of researched T-joints. The loading plates were modelled by using an analytical rigid plate with a reference point for numerical analysis convenience. The typical finite element mesh of T-joint is shown in Fig.7.

The real material model in the ABAQUS library was used in the finite element analysis. The initial part of the bilinear curve represents the elastic property up to the tensile yield stress (f_y) with measured elastic modulus (E) and Poisson's ratio (ν). The post-yield response of the bilinear material model was developed based on the measured ultimate tensile stress (f_u) and elongation after fracture (ε_f) obtained from the standardized coupon tests for S455, while the Von-Mises yield criterion and kinematic hardening model were applied. The material nonlinearity behaviour was included in the finite element models.

A comparison between the test and FEA results was carried out to validate the FEM models. In frames of this contribution only validation for joints subjected to action of compression are discussed as being more suitable for development of considered benchmark cases and appropriate FEM models. The joint strengths and failure modes of chosen type of the specimens were investigated at 3% b_0 deformation level according to [1, 3]. The comparison of the joint load-displacement curves obtained from the tests and finite element analysis is shown in Fig.8. Good agreement between the test and finite element analysis results was achieved on allowed deformation level with the maximum difference of 10,3% and the minimum difference of 2.6%. It is shown from the comparison that the finite element analysis results generally agreed with the test results. Therefore, it was demonstrated that the newly developed finite element models success fully predicted the structural behaviour of researched types of T-joints.

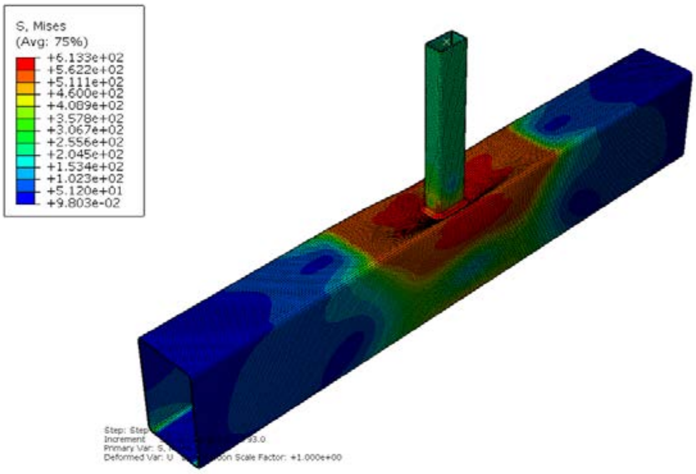


Fig.7. Typical finite element mesh and equivalent stresses

4. BRIEF CONCLUSIONS

Schemes of gauges equipment adopted for the test specimens provide a basis for the numerical FEM model verification.

Experimental patterns of failure and force-displacement curves for the specimens correspond to the FEM outcomes in a good manner.

Comparative analysis of the tests` data and the outcomes obtained after analysing of finite element model developed by means of ABAQUS CAE software reflects an acceptable convergence. This fact enables using ABAQUS CAE in further investigations for the obtaining a parametrical model of the offset T-joints behaviour and development of implicit expressions for evaluation of their bearing capacity and design.

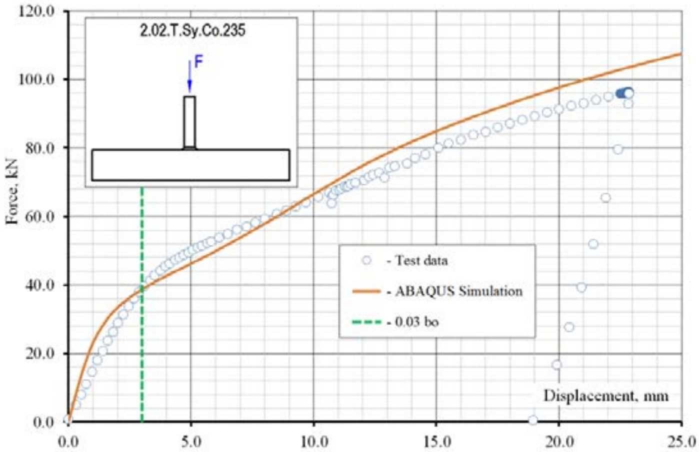


Fig.8. Comparative analysis of test data and FEM outcomes

Obtained results of the first test series are intended to use for parametric analyses and development of practical design guideline for offset joints and connections.

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