

Full length article

Distortions and residual stresses of NSS, HSS and hybrid box sections with single-bevel butt welds: An experimental study

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ABSTRACT

A comprehensive experimental study, focusing on distortions and residual stresses, is conducted on a total of nine box sections with single-bevel butt welds consisting normal strength steel (S355MC), high strength steel (S700MC), and hybrid (NSS-HSS) sections. Dimensional analysis is carried out and the calculated Rosenthal numbers indicate the use of fast MAG welding heat sources, validating the assumption of uniaxial residual stresses. Strain gauge measurements during welding reveals the ratio of maximum welding-induced compressive strains in the flange and web depending on the width-to-thickness ratio. Measured maximum out-of-flatness is closely matching the $B/200$ recommendation for equivalent geometric imperfections in panels according to EN 1993-1-5 suggesting that a modification of local imperfection limits in welded box sections is needed. The contour method is successfully used to evaluate manufacturing-induced longitudinal residual stress fields, designating a novel application for box sections. Compressive stresses show a clear decreasing trend with increasing thickness. Furthermore, compressive residual stress variation due to pre-welding manufacturing steps is assessed based on the difference between measured welding-induced and manufacturing-induced membrane residual stresses. In addition, a novel residual stress model is developed for NSS, HSS, and hybrid box sections with single-bevel butt welds, incorporating manufacturing parameters such as heat input, weld seam area, number of weld passes, filler material strength, and steel grades of the base material.

1. Introduction

Nowadays, there is a strong demand to speed up and ensure the quality of manufacturing. It is important to highlight that each step of manufacturing inevitably induces residual stresses and geometric imperfections in the workpiece, which ultimately affect the lifetime and performance of the product. These must be taken into consideration in the design, fabrication, and construction. Previous research, e.g., [1], emphasized the influence of residual stresses and geometrical imperfections on the load bearing capacity of structural elements. The determination of buckling resistance during the design phase is a cardinal issue since instability of a structural member may be critical in the life of a structure. Generally, designers are supported by buckling curves recommended by standards, which indirectly include the effects of imperfections due to manufacturing. Previous research shows that standards may overestimate the buckling resistance in several cases during stability design. However, there are recommendations in the international literature for using modified buckling curves [2] or partial safety factors [3] in order to obtain reliable design. On the other hand, advanced

design approaches, e.g., geometrically and materially nonlinear analysis with imperfections according to EN 1993-1-5 [4], require information on magnitudes of geometrical imperfections and typical residual stress distributions. To address these effects, standards give only approximations. Basically, initial distortions in the numerical models may be defined regarding the manufacturing tolerances given in standards. In addition, application of simplified residual stress models is limited to typical cross-sectional layouts, steel grades and geometrical dimensions, while manufacturing specialities are not taken into consideration directly.

Normal and high strength steels are mainly used separately in steel girders; however, the application of high strength steels (above yield strength of 360 MPa) and ultra-high strength steels (above yield strength of 690 MPa) makes it possible to save resources, reduce self-weight, and manufacture more slender and economic structures. Nevertheless, economical design can only be performed if high strength steel parts can be utilised efficiently; thus, a hybrid girder consisting of different steel grades in the web and flanges is a possible compromise [5]. Unfortunately, the use of hybrid girders is fairly limited in the civil engineering

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practice since EN 1993–1–1 [6] does not include a design approach for hybrid girders. Several experimental programs dealing with hybrid I-girders have been carried out in the 60's and 70's [7–9], while lately they come to the front [10,11] due to economical purposes. In general, theoretical analysis have been published [12–14] for describing the structural behaviour of hybrid girders subjected to e.g., pure bending, combined shear and bending, shear buckling, lateral-torsional buckling, etc.

In manufacturing of steel structures, welding has become the leading joining process. Importance of welding has increased lately, because of the varied structural designs and the diversity of material characteristics. Welding has also become more and more relevant in on-site constructions due to the development of welding processes, while it has been widely used in workshops for a long time. Welded box sections are widely used in industrial hall structures, stadiums, bridges [17], light-weight canopy roofs with compression ring [18], and high-rise buildings in seismic areas [19] in the civil engineering practice (Fig. 1). Behaviour of welded box sections has been already analysed from a variety of aspects. For instance, developments in the field of material science and manufacturing technology resulted in using base material with higher yield strength [20–22], while developments in design theory resulted in novel design approaches [3,23–25]. On the other hand, box sections can be used in innovative structural systems such as concrete-filled steel columns. Square and rectangular cross-sections are becoming increasingly common in the construction industry [26], due to the simpler design of column-beam connections, the significant bending resistance of the cross-section and aesthetic considerations. In addition, structural behaviour at elevated temperature has been investigated as well in the past years [27,28]. Notations and typical configurations, i.e., weld and joint types according to EN ISO 2553, of welded box sections mentioned in the current paper are shown in Fig. 2.

The current paper is organized as follows. Section 2 gives a review of

state-of-the-art residual stress models of welded box sections. In Section 3, the experimental research program is summarized, while Section 4 focuses on residual stress measurement results using contour method. A novel unified residual stress model is developed, which can be used for NSS, HSS and hybrid welded box sections; it is presented in Section 5. Finally, Section 6 addresses further comments and discussion.

2. Literature review

Since the current paper is focusing on welding-induced residual stresses of welded hybrid box sections, consisting of both normal strength steel and high strength steel plates, the literature review summarizes the most important residual stress measurement results and simplified residual stress models.

Longitudinal residual stresses of welded box sections were measured by several researchers in the past decades. The analysed dimensions and applied weld types (Fig. 2), yield strength f_y (for NSS) or proof strength $f_{p0.2}$ (for HSS) of base material, and residual stress measurement techniques in conjunction with the main contribution of the referenced publications are summarized in Table 1. Experimental studies of normal strength steel welded box sections, below specified minimum yield strength of 360 MPa according to ISO TR 15608, dealing with residual stresses were carried out in several studies considering different steel grades and width-to-thickness ratios. Outer cross-sectional dimensions of the previously investigated specimens varied between 80×80 and 414×414. Minimum plate thickness was 4 mm, while maximum thickness was 12.7 mm (thus, ½ in). Yield strength of the NSS base plates varied between 250 MPa and 414 MPa. Moreover, tensile tests showed the classical yielding plateau with hardening even for the highest yield strength in the list [29]. There are only a few studies available in the literature that focus on the experimental investigation of welding-induced residual stresses in high strength steel box sections



Fig. 1. Application of welded box sections in a) high-rise buildings [15], b) stadium [16] and c) arch bridge [17].

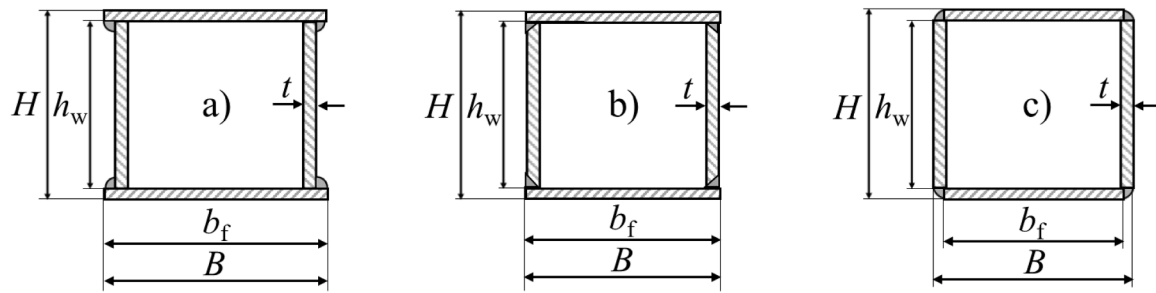


Fig. 2. Notations of typical welded box sections: a) angle joints with fillet welds, b) corner joints with single-bevel butt welds and c) corner joints with fillet welds.

Table 1

Summary of residual stress measurements of NSS and HSS welded box sections.

Publication	$B \times H$ [mm ²]	t [mm]	f_y or $f_{p0.2}$ [MPa]	Weld type	Measurement technique	Main contribution
[32]	127×127 152×152 229×229 254×254	6.4 12.7	250	square butt/ single-bevel butt	sectioning technique (Whittemore strain gauge)	a) edge preparations such as machining or flame cutting have little effect on residual stresses of welded box sections, b) welding heat input increases the yield strength in the vicinity of welds
[33]	292×292 414×414	6.4	266 273	square butt	sectioning technique (Whittemore strain gauge)	higher tensile residual stresses are induced due to filler material with higher strength
[34]	160×200	4	373	fillet	sectioning technique (electrical strain gauges)	average of tensile residual stresses in the vicinity of welds reached the level of measured yield strength
[19]	500×500 700×700	28 45	338–400	single-bevel butt (partial/full)	sectioning technique (Whittemore strain gauge)	a) residual stresses are not symmetric with respect to the two symmetry axes of the box column, b) welding side has higher residual stress than that the non-welding side c) full penetration welding induces higher residual stresses
[29] and [22]	80×80 120×120 150×150 170×170 180×180 195×195 220×220 250×250	4 5 6 8	318–1005	single-bevel butt	sectioning technique (electrical strain gauges)	a) compressive residual stresses are highly influenced by the width-to-thickness ratio and plate thickness, b) b) magnitude of tensile residual stress is equal to yield strength for all specimens analysed in this work
[21]	111×111 157×157 220×220	11	506	single-bevel butt	sectioning technique (Whittemore strain gauge) and hole-drilling method	width of tension zones differs in flange and web in the case of single-bevel butt welds
[35]	100×100 140×140 150×150 240×240 330×330 380×380	10 12 14	506	single-bevel butt	sectioning technique (Whittemore strain gauge)	stress distribution shape of NSS and HSS box sections is similar
[36]	75×75 100×100 125×125 200×200 240×240 400×400	5 16	690	fillet	neutron diffraction technique	magnitudes of tensile and compressive residual stresses can be similar among light welded and heavy welded box sections

with specified minimum yield strength of 360 MPa; such studies are also summarized in the table. Outer cross-sectional dimensions of the HSS specimens varied between 80×80 and 400×400. Minimum plate thickness was 4 mm, while maximum thickness was 16 mm. Proof strength of the base plates varied between 506 MPa and 1005 MPa. It is highlighted that residual stress measurements and thus typical residual stress distribution of hybrid welded box sections are not published yet according to the Authors' knowledge.

Residual stress measurement techniques fall into three categories: destructive, semi-destructive, and non-destructive [30]. Destructive and semi-destructive methods, also known as mechanical methods, rely on the measurement of post-material removal deformations [31]. Non-destructive techniques assess parameters associated with residual stress damaging the specimen [30]. Four approaches were applied for

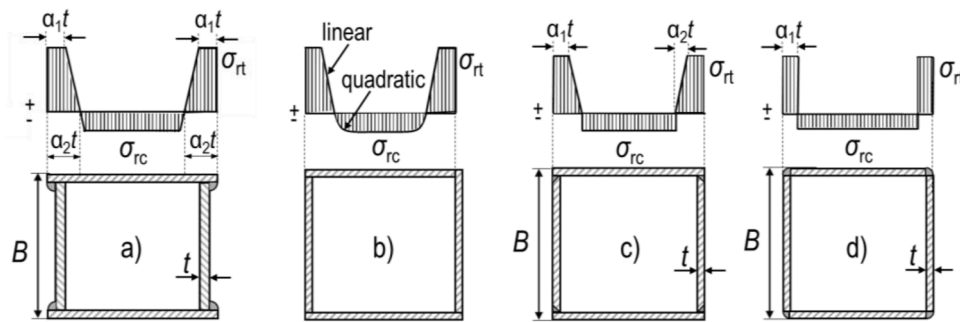
measuring residual stresses in welded box sections: (i) mechanical strain measurement (Whittemore strain gauge) after the conventional sectioning technique (destructive) on steel strips with gauge holes, (ii) continuous electrical resistance measurement (uniaxial strain gauges) during and after transverse and longitudinal cuts of the modified sectioning technique (destructive), (iii) hole-drilling method (semi-destructive) and (iv) neutron diffraction technique (non-destructive).

A total of six longitudinal residual stress models is gathered in Table 2 which are applicable for NSS and HSS welded box sections. The table summarizes model type, parameters and the application criteria as well, while the schematic drawings of model types are shown in Fig. 3. In 1976, ECCS [1] recommended a residual stress model for resistance calculations of welded box sections derived from experimental results and theoretical considerations, e.g., the concept of tendon force due heat

Table 2

Summary of residual stress models of NSS and HSS welded box sections (N/A: not available).

Publication	Model type	Model parameters	Criteria
ECSS [1]	Model 1	Light/heavy welds B/t 10 α_1 0 α_2 from equilibrium σ_{rt} f_y σ_{rc} $0.60f_y$	joints: N/A welds: N/A base material: N/A t N/A $10 \leq B/t \leq 40$
BSK 99 [38]	Model 1	$\alpha_1 = 1.5, \alpha_2 = 3.0$ $\sigma_{rt} = \min(f_y, 500 \text{ MPa})$ σ_{rc} based on equilibrium	joints: N/A welds: N/A base material: N/A $t \leq 40 \text{ mm}$ $B/t \geq 6$ N/A
Chinese code [39]	Model 2	$\sigma_{rt} = f_y$ $\sigma_{rc} = 0.53f_y$	N/A
Kövesdi and Somodi [22]	Model 3	$\alpha_1 = 2.5$ for S235 $\alpha_1 = 2.0$ for S355-S460 $\alpha_1 = 1.5$ for S500 $\alpha_1 = 0.75$ for S700 $\alpha_1 = 0$ for S960 $\alpha_2 = \frac{B - t - 2\alpha_1 t - \frac{\sigma_{rt}(B - t - 2\alpha_1 t)}{2 \sigma_{rc} + \sigma_{rt}}}{2t} \text{ for S235-S960}$ $\sigma_{rt} = f_y$ (NSS) or $\sigma_{rt} = f_{p0.2}$ (HSS) $\sigma_{rc} = 70 - 20t + t^2 - [2900 - 3600(t-5)] \times [B/t]^{-1}$ for $t \leq 5 \text{ mm}$ $\sigma_{rc} = 70 - 20t + t^2 - [2900 - 290(t-5)] \times [B/t]^{-1}$ for $t > 5 \text{ mm}$	joints: corner welds: single-bevel butt base material: S235-S960 $4 \text{ mm} \leq t \leq 8 \text{ mm}$ $16 \leq B/t \leq 62.5$
Ban et al. [35]	Model 1	$\sigma_{rt} = f_y$ $\sigma_{rc} = -10 - 1500 \frac{t}{B-t} - 550 \frac{1}{t}$ $\alpha_1 t = t + 0.05(B-t)$ $\alpha_2 t$ from equilibrium and geometry	joints: corner welds: single-bevel butt base material: Q460 $10 \text{ mm} \leq t \leq 14 \text{ mm}$ $10 \leq B/t \leq 38$
Khan et al. [36]	Model 4	$\sigma_{rt} = 1.07f_y$ for $t = 5 \text{ mm}$ $\sigma_{rt} = 1.07f_y$ for $t = 16 \text{ mm}$ $\sigma_{rc} = 3.6607f_y \left(\frac{B-t}{t} \right)^{-0.924}$ $\alpha_1 = \frac{(B-t)\sigma_{rc}}{2t(\sigma_{rt} + \sigma_{rc})}$ Width of compressive zone from equilibrium	joints: corner welds: fillet base material: S690 $t = 5 \text{ and } 16 \text{ mm}$ $16 \leq B/t \leq 41$

**Fig. 3.** Residual stress model types: a-d) Models 1–4.

input during welding, which is in equilibrium with the resultant of compressive residual stresses. Different parameters were evaluated for light (single-pass welds) and heavy (multi-pass welds) welded sections, and varying width-to-thickness ratios in order to somehow distinguish and consider distinct amount of welding and cross-sectional dimensions. On the one hand, magnitude of tensile residual stresses, in the vicinity of the welds, are equal to yield strength, while compressive residual stresses are fixed values for each layout. The prEN 1993-1-14 [37] standard implemented the aforementioned model as well. On the other hand, the Swedish design standard [38] does not make any distinction between variant weld sizes or cross-sectional dimensions. However, the compressive residual stresses are not fixed and recommended to calculate based on equilibrium equation. In addition, the recommended model of the Chinese standard [39] uses a quadratic distribution in the compressive zone, with a fixed magnitude of $0.53f_y$ independent from B/t ratio and manufacturing specialities, combined with a linear

variation in the tensile zone. Maximum tensile residual stress is equal to the yield strength as well. In 2018, Somodi and Kövesdi [22] proposed an advanced residual stress model, for welded box sections with structural steel grade up to S960 based on measurement results, that takes yield strength, plate thickness and B/t ratio directly into account in determining model parameters. In 2012, Wang et al. [40] focused on the magnitude and distribution of residual stresses in Q460 box sections. Based on the experimental results, a simplified residual stress distribution was suggested. In 2013, Ban et al. [41] investigated the residual stress distributions of six welded box sections fabricated from Q460 structural steel, and a residual stress model was proposed based on measurement results. Khan et al. [36] analyzed residual stresses of box sections, with light and heavy welds, fabricated from structural steel with nominal yield strength of 690 MPa in 2016. As the main outcome of the research, a simplified model was proposed for HSS box sections.

A comprehensive literature review is carried out focusing on

previous experimental welding-induced residual stress results of NSS and HSS welded box sections, while available residual stress models and proposals are summarized as well. However, it can be concluded that there are no residual stress measurements, available residual stress distributions or residual stress models regarding hybrid welded box sections in the literature, which shows the novelty and relevance of the current study to overcome previous limitations.

3. Experimental research program

The experimental study investigates a total of nine specimens (Fig. 4) including one normal strength steel, five high strength steel and three hybrid welded box sections. The experimental program consists of the following measurements and analyses:

- thickness measurements,
- analysis of mechanical properties and chemical composition based on inspection certificates,
- registration of welding variables,
- measurement of weld pool length and width for dimensional analysis,
- macroscopic examinations,
- transient strain measurements during welding,
- shape measurements,
- and two-dimensional full-map residual stress measurements after manufacturing using contour method.

3.1. Welded specimens

Nominal width and height of the specimens are 200 mm and 220 mm, specimen lengths are 700 mm and 800 mm, while plate thicknesses are 4, 6 and 8 mm. Three specimen groups are divided based on plate thickness, namely RS4, RS6 and RS8, respectively. Sketch and measured main dimensions of the investigated specimens are shown in Fig. 5. Length L , diagonals d_1 and d_2 and widths B_1 and B_2 of the constituent plates are measured with a tape measure, thickness measurement of plate thicknesses t_1 and t_2 is carried out with a digital caliper. At least three measurements are carried out for determining each parameter, and the average value is evaluated. Lower indices 1 and 2 correspond to the webs and flanges, respectively. Normal strength steel plates are manufactured from thermomechanically rolled fine grained structural steel S355MC (alloy quality steel according to EN 10020) with ferritic-pearlitic microstructure. On the other hand, thermomechanically

rolled and micro-alloyed S700MC (alloy special steel according to EN 10020) steel grade, with ferritic-bainitic fine grained microstructure in as-received condition, is applied for high strength steel plates. Mechanical properties of base materials, namely yield strength f_y of proof strength $f_{p0.2}$, ultimate strength f_u , and percentage total extension at fracture A are summarized in Table 3 according to the inspection certificates. Requirements of the corresponding EN 10149-2 standard are fulfilled. Chemical composition of base materials, according to inspection certificates, are summarized in Table 4.

Plasma cutting is applied for carving the constituent plates. Corner joint is used with single-bevel butt weld with broad root face. Edge preparation of web plates (Fig. 6) is performed as specified in the corresponding Welding Procedure Specification (WPS). Bevel angle is 45° , no root opening is applied, while root face is 1 mm. Tack welds are used for assembling the specimens. Each joint is welded manually in PA flat welding position with one or two weld passes for thickness $t \leq 6$ mm and $t > 6$ mm, respectively (Fig. 6). The applied welding process is metal active gas (MAG) welding with solid wire (135). Each joint is welded with one weld pass in PA flat welding position according to EN ISO 6947. A Fronius Trans SynSteel 5000 welding power source is used with direct current and reverse polarity (DC+). The type of the shielding gas during manufacturing is M21 - ArC - 18 (Corgon 18 with 82 % Argon + 18 % CO₂) mixed gas with gas flow rate of 14 l/min, while solid wire is Mn3Ni1Mo (EN ISO 16834) WDI MoNi SG with a diameter of 1.2 mm and a guaranteed minimum proof strength and ultimate strength of 690 MPa and 770 MPa, respectively according to the inspection certificate. No preheating is applied, interpass temperature is 250°C , while ambient temperature is between $24.1 - 31.0^\circ\text{C}$ during manufacturing. Tables 5-7 summarizes registered welding variables and welding sequence. The table includes the weld pass number #, welding current I , voltage U , travel speed v and heat input $q = \eta UI/v$, where thermal efficiency η is 0.80 for MAG welding based on EN 1011-1. Welding direction is the same for all the welds.

3.2. Dimensional analysis

Size and shape of characteristic isotherms play a crucial role in determining whether the heat source is moving fast or slow [42], while geometry of the melting isotherm influences critical aspects such as weld seam geometry and metallurgical dilution [43]. Moreover, shape of the isotherms determines the relative magnitude of gradients in the thermal stress field; large gradients in the direction perpendicular to heat source movement allow for the assumption of simplified uniaxial model of thermal and residual stresses [44]. In this manner, weld pool and the

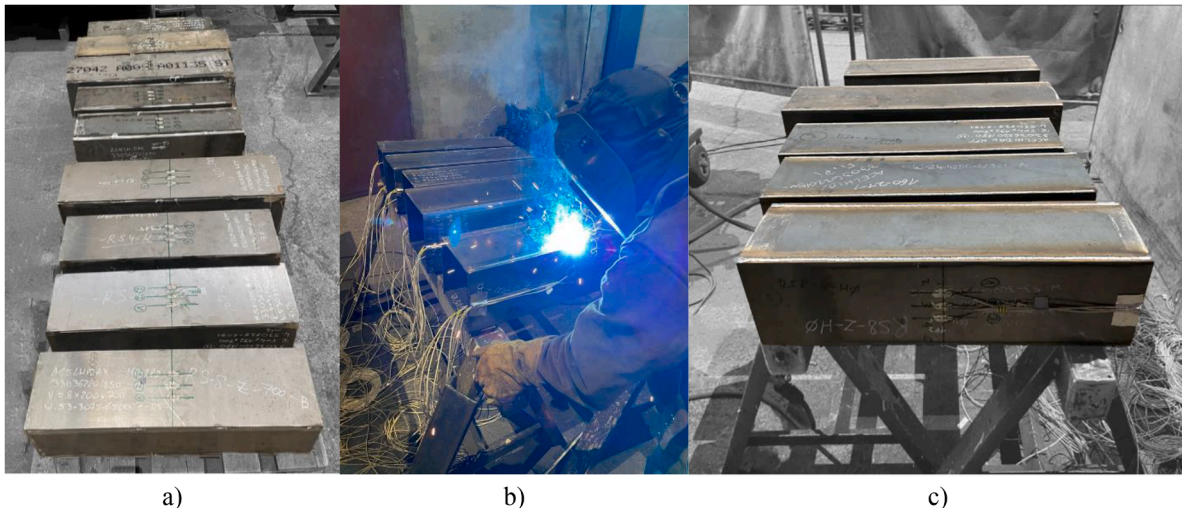
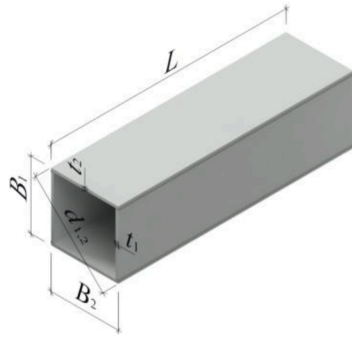


Fig. 4. Photos of box sections: a) before welding, b) during welding and c) after manufacturing.



Specimen	Steel grade		L [mm]	t_1 [mm]	t_2 [mm]	B_1 [mm]	B_2 [mm]	d_1 [mm]	d_2 [mm]
	web	flange							
RS4-700A	S700MC	S700MC	698.8	4.17	4.11	199	200	280	281
RS4-700B	S700MC	S700MC	699.5	4.10	4.10	200	200	280	281
RS4-H	S700MC	S355MC	698.5	4.11	4.16	198	199	279	279
RS6-355	S355MC	S355MC	799.0	6.20	6.19	219	220	310	310
RS6-700	S700MC	S700MC	798.5	6.10	6.17	220	219	310	309
RS6-H	S700MC	S355MC	798.5	6.10	6.17	220	219	309	309
RS8-700A	S700MC	S700MC	697.8	8.07	7.97	200	199	280	280
RS8-700B	S700MC	S700MC	698.5	7.98	8.00	198	199	280	280
RS8-H	S700MC	S355MC	698.5	7.94	7.94	200	199	281	281

Fig. 5. Sketch and measured dimensions of the investigated specimens.

Table 3

Mechanical properties of base materials according to inspection certificates.

Steel grade	f_y [MPa]	$f_{p0.2}$ [MPa]	f_u [MPa]	A [%]
S355MC – t4	402	-	469	37
S355MC – t6	446	-	570	27
S355MC – t8	400	-	486	30
Requirement (EN 10149-2)	≥ 355	-	430–550	≥ 23
S700MC – t4	-	746	829	22
S700MC – t6	-	749	833	20
S700MC – t8	-	738	827	22
Requirement (EN 10149-2)	-	≥ 700	750–950	≥ 12

resulting solidified weld bead are practical indicators, as demonstrated in [42] and [45], as their size and shape can be measured after welding, while could be also used for the calibration of heat source models in welding simulation [46]. The associated overall aspect ratios $AR = l_w/w_w$ for the isotherms associated with liquidus temperature T_{liq} , are evaluated by fitting semi-ellipsoids to the weld pool using AutoCAD, where l_w is weld pool length and w_w is weld pool width (Fig. 7a). AR together with the dimensionless Rosenthal number Ro (Eq. 1) can be used for classifying the MAG welding heat sources applied during manufacturing. To evaluate aspect ratios, weld seams were documented through photography with semi-ellipsoids fitted to the weld pool using AutoCAD (Fig. 7a). The Rosenthal number is calculated as follows [44], assuming two-dimensional (2D) heat transfer instead of a three-dimensional (3D) problem, for the investigated thin-walled sections:

$$Ro = \frac{Q}{2\pi\lambda t\Delta T_c} \quad (1)$$

where $Q = \eta UI$ is net heat source power considering thermal efficiency, λ is effective thermal conductivity, t is plate thickness, while $\Delta T_c = T_c - T_0$

is temperature difference from the initial or preheat temperature T_0 in the region of interest. A heat source is classified as fast when advection (heat transfer due to the movement of the solid) significantly outweighs conduction ($Ro \gg 1$) and as slow when conduction dominates over advection ($Ro \ll 1$) [44]. In this paper, Rosenthal number Ro is calculated for the evaluation of the weld pool by setting $T_c = T_{liq} = 1525^\circ\text{C}$ for the analysed steel grades with low carbon content, while other parameters are $T_0 = 20^\circ\text{C}$ and $\lambda = 33.6 \text{ W/(m}\cdot\text{K)}$. The corresponding weld pool dimensions, aspect ratio, and Rosenthal number values are summarized in Tables 5,6,7. For practical reasons, only the values for the second weld passes within a weld seam are shown for the RS8 specimen group, as the first weld pass is fully covered. Rosenthal numbers and aspect ratios are all slightly above 1, while the values are quite close ($AR \approx Ro$) which is in accordance with the assumption of using the simplified fast asymptotic expression; details can be found in [47]. In addition, aspect ratios are plotted against Rosenthal numbers in Fig. 7b. A quantitative limit for application of the uniaxial stress assumption is formulated in [48,49] such that $AR^2 \geq 2(1 + \nu)$, where ν is Poisson's ratio. For the investigated steel grades, ν is assumed to be 0.3 yielding $AR \geq 1.6$ which is true for twenty-six out of the thirty-two evaluated weld seams. The analysed cases appear to be mostly within the transition zone, with some extending slightly into the fast regime, indicating that the assumption of uniaxial residual stresses is valid in general as a simplification.

3.3. Macroscopic examinations

Macroscopic examinations are carried out in accordance with EN 12345. Test specimens include unaffected base material, heat-affected zone (HAZ) and weld metal (WM) as well. Typical macrographs for each specimen group are shown in Fig. 8. Typical dimensions, such as excess weld metal, maximum throat thickness, cross-sectional area of the weld metal A_w , etc., are evaluated as well and summarized in

Table 4

Chemical composition of base materials according to inspection certificates.

Steel grade	C %	Si %	Mn %	P %	S %	Al %	Nb %	V %	Ti %	Cu %	Cr %	Ni %	Mo %	B %	N %
S355MC – t4	0.062	0.01	0.59	0.009	0.003	0.042	0.025	0	0	0.010	0.030	0.04	0	0.0001	0.002
S355MC – t6	0.056	0.01	0.70	0.009	0.004	0.036	0.029	0.006	0.001	0.011	0.018	0.01	0.006	-	0.0062
S355MC – t8	0.061	0.01	0.69	0.011	0.004	0.028	0.027	0.006	0	0.011	0.050	0.03	0.003	0.0001	0.0050
Requirement (EN 10149-2)	≤ 0.12	≤ 0.50	≤ 1.50	≤ 0.025	≤ 0.020	≥ 0.015	≤ 0.09	≤ 0.20	-	≤ 0.15	-	-	-	-	-
S700MC – t4	0.059	0.02	1.84	0.009	0.002	0.05	0.061	0.010	0.110	0.01	0.03	0.04	0.01	0.0001	0.005
S700MC – t6	0.055	0.03	1.93	0.014	0.002	0.039	0.052	0.051	0.099	0.019	0.05	0.03	0.007	0.0002	-
S700MC – t8	0.062	0.02	1.83	0.011	0.002	0.058	0.063	0.010	0.100	0.01	0.02	0.03	0.1	0.0001	0.004
Requirement (EN 10149-2)	≤ 0.12	≤ 0.60	≤ 2.10	≤ 0.025	≤ 0.015	≥ 0.015	≤ 0.09	≤ 0.50	-	≤ 0.22	-	-	≤ 0.50	≤ 0.0005	-

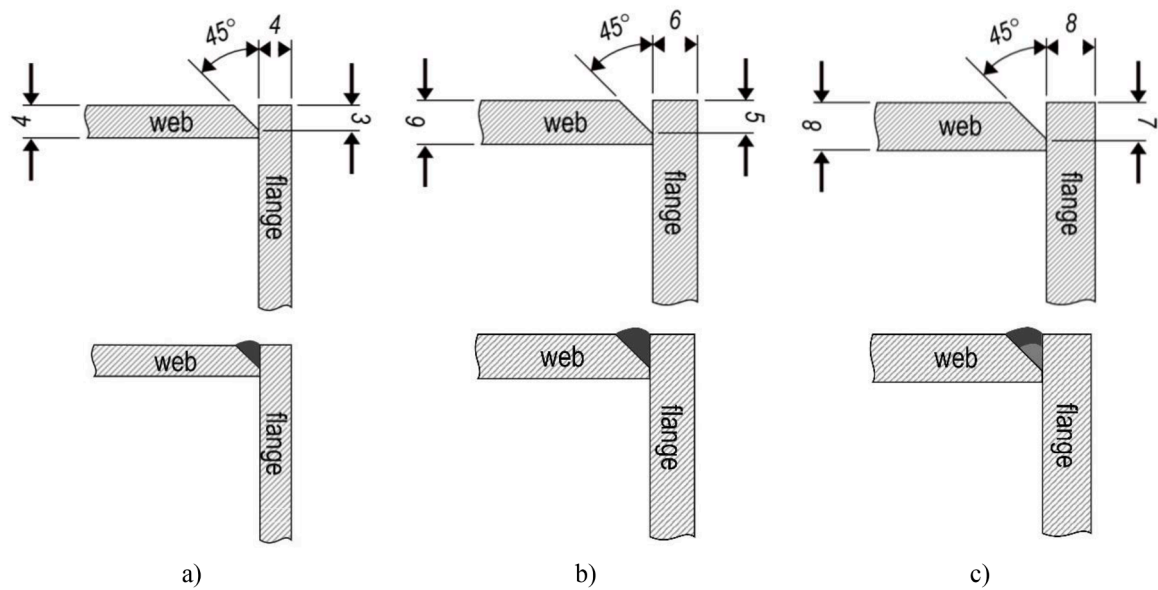


Fig. 6. Edge preparation of the plates and number of weld passes: a) RS4 b) RS6 and c) RS8 specimen groups.

Table 5
Welding variables, weld pool dimensions and dimensionless quantities of the RS4 specimen group.

Welding sequence	Specimen	#	–	I [A]	U [V]	v [mm/s]	q [kJ/mm]	l_w [mm]	w_w [mm]	AR [-]	Ro [-]
i j k l	RS4-700A	1	k	220	19.5	7.45	0.46	17.5	8.4	2.1	2.7
		2	i	205	19	7.78	0.40	17.6	7.8	2.3	2.5
		3	j	192.5	18.5	7.78	0.37	18.0	7.8	2.3	2.2
		4	l	200	18.5	8.14	0.36	17.1	9.0	1.9	2.3
	RS4-700B	1	i	200	20.25	9.59	0.34	16.4	9.0	1.8	2.5
		2	k	225	21.25	10.77	0.36	18.0	9.2	2.0	3.0
		3	l	215	20.75	10.14	0.35	15.3	8.2	1.9	2.8
		4	j	215	20.25	10	0.35	20.9	8.0	2.6	2.7
	RS4-H	1	i	215	20.75	10.61	0.34	17.4	7.8	2.2	2.8
		2	k	215	20.75	12.28	0.29	16.4	8.6	1.9	2.8
		3	l	215	20.75	10.61	0.34	14.6	7.2	2.0	2.8
		4	j	207.5	20.25	9.86	0.34	20.9	8.2	2.5	2.6

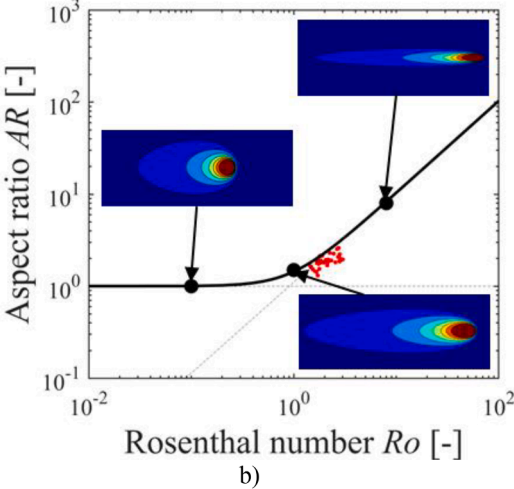


Fig. 7. a) Weld pool length and width; b) evaluated aspect ratios plotted against Rosenthal numbers (indicated by red dots) in relation with slow and fast regimes as referred to in [44].

Table 8.

3.4. Transient strain measurements during welding

Strain measurement with electrical strain gauges is carried out during welding (Fig. 4b) which can provide essential data on the amount of

Table 6

Welding variables, weld pool dimensions and dimensionless quantities of the RS6 specimen group.

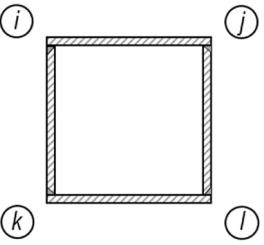
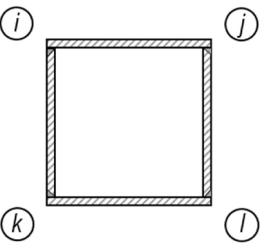
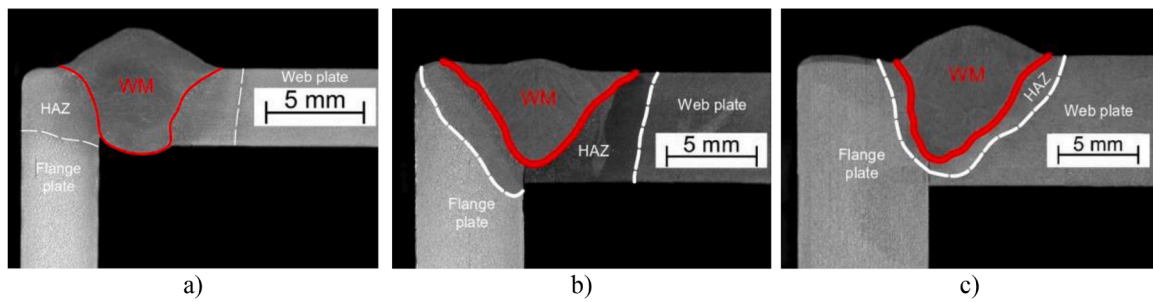
Welding sequence	Specimen	#	–	I [A]	U [V]	v [mm/s]	q [kJ/mm]	l_w [mm]	w_w [mm]	AR [-]	Ro [-]
	RS6-355	1	i	215	20.5	6.25	0.56	19.3	10.2	1.9	1.8
		2	k	210	20.25	6.2	0.55	21.0	11.2	1.9	1.8
		3	j	222.5	19.25	6.61	0.52	20.5	9.6	2.1	1.8
		4	l	225	20.75	6.72	0.56	19.9	11.0	1.8	2.0
	RS6-700	1	k	215	19.5	5.59	0.60	17.9	10.0	1.8	1.8
		2	i	215	20	6.5	0.53	21.9	12.2	1.8	1.8
		3	j	215	19.75	6.11	0.56	20.4	10.8	1.9	1.8
		4	l	225	20	6.4	0.56	21.0	9.8	2.1	1.9
	RS6-H	1	i	222.5	23.25	7.77	0.53	19.1	9.8	2.0	2.2
		2	k	215	22.75	7.55	0.52	19.8	10.2	1.9	2.1
		3	l	225	22.75	7.69	0.53	18.9	10.4	1.8	2.1
		4	j	222.5	22.75	7.41	0.55	17.9	10.6	1.7	2.1

Table 7

Welding variables, weld pool dimensions and dimensionless quantities (where applicable) of the RS8 specimen group.

Welding sequence	Specimen	#	–	I [A]	U [V]	v [mm/s]	q [kJ/mm]	l_w [mm]	w_w [mm]	AR [-]	Ro [-]
	RS8-700A	1	k	197.5	18.5	9.33	0.31	–	–	–	–
		2	i	197.5	18.5	9.59	0.30	–	–	–	–
		3	j	187.5	18.75	10.94	0.26	–	–	–	–
		4	l	195	18.5	8.54	0.34	–	–	–	–
		5	k	225	20.5	7	0.53	18.3	11.0	1.7	1.5
		6	i	230	20.5	7.22	0.52	18.3	11.4	1.6	1.5
		7	j	235	21.75	7.87	0.52	16.0	11.0	1.5	1.6
		8	l	235	22.5	8.24	0.51	16.6	11.6	1.4	1.7
	RS8-700B	1	i	200	20.25	12.73	0.25	–	–	–	–
		2	k	202.5	20.25	11.86	0.28	–	–	–	–
		3	l	205	20.25	9.86	0.34	–	–	–	–
		4	j	195	20.25	11.29	0.28	–	–	–	–
		5	i	222.5	24.25	8.14	0.53	18.0	9.8	1.8	1.7
		6	k	227.5	24.25	7.69	0.57	20.1	11.2	1.8	1.7
		7	l	217.5	24.25	8.43	0.50	19.1	9.8	2.0	1.7
		8	j	225	24.75	7.22	0.62	18.9	10.8	1.7	1.8
	RS8-H	1	k	215	21.75	12.96	0.29	–	–	–	–
		2	i	205	20.75	11.11	0.31	–	–	–	–
		3	j	205	20.25	11.48	0.29	–	–	–	–
		4	l	205	20.25	10.61	0.31	–	–	–	–
		5	k	205	23.75	7.53	0.52	13.8	9.0	1.5	1.5
		6	i	220	24.25	7.61	0.56	17.9	10.0	1.8	1.7
		7	j	220	24.75	8.05	0.54	13.9	10.6	1.3	1.7
		8	l	232.5	24.25	8.14	0.55	15.8	10.2	1.5	1.8

**Fig. 8.** Macrographs of a) RS4-700A, b) RS6-H and c) RS8-H specimens.

deformation and residual stresses that occur during welding. In the experimental setup, Kyowa uniaxial strain gauges (KFGS-3-350-C1-11 with nominal resistance of 350 Ω) are connected to HBM MGCplus data acquisition system via an HBM Canhead amplifier system. During the measurement, axial strains are continuously displayed on a laptop in HBM CatmanEasy software. A sampling rate of 5 Hz is applied during data acquisition. Cold curing adhesive is used for the strain gauge installation with temperature limit between -50 $^{\circ}\text{C}$ and $+120$ $^{\circ}\text{C}$. Strain gauges are placed in the midsection of specimens. Measurements are carried out only on two sides of the specimens. Strain gauges are denoted by F1-F4 on the flange and W1-W4 on the web, respectively. Six

strain gauges (F1-F3 and W1-W3) are installed on the outer surfaces and two strain gauges (F4 and W4) are used on the internal surfaces. It is very important that conventional strain gauges should be placed at an appropriate distance from the high temperature zone of the weld to ensure their integrity. Locations of measuring points are determined based on precalculations by using data given in the WPS and are summarized in Fig. 9. Measured signals are presented in the figure as well for specimen RS6-355 indicating four dominant peaks for the four weld passes, while evolution of axial strains during cooling to ambient temperature begins after approximately 4000 s.

Measured final strain values at room temperature after cooling of the

Table 8

Geometrical dimensions of welds based on macrographs.

Specimen	Area of weld metal A_w [mm ²]	Max. throat thickness [mm]	Width of HAZ [mm]	Width of WM [mm]	Excess weld metal [mm]
RS4-700A	28.4	6.4	11.3	8.2	2.1
RS4-700B	17.5	4.3	10.4	7.6	1.6
RS4-H	22.3	5.5	10.3	8.1	1.1
RS6-355	32.4	5.5	13.1	10.1	0.9
RS6-700	23.5	5.0	11.3	9.3	1.5
RS6-H	29.7	5.8	13.2	10.8	0.5
RS8-700A	28.7	5.6	11.5	10.0	1.4
RS8-700B	35.1	6.6	11.9	10.3	1.6
RS8-H	45.9	8.4	11.7	9.5	2.1

specimens are assessed for each strain gauge. Thus, residual strains induced solely by welding are summarized in Table 9 and Fig. 10. At first glance, the absolute value of measured strains in the web is significantly smaller than in the flanges. Strains are therefore assessed based on distinct criteria in the following paragraphs.

Welding-induced residual strain ranges of different width-to-thickness ratio B/t and different steel grades are summarized in Fig. 11 using box charts in Matlab [50], where the following information are displayed: the median, the lower and upper quartiles, any outliers (applying $1.5 \times$ interquartile range as a reference in the software), and the minimum and maximum values that are not outliers. These statistical data, based on a total of $9 \times 8 = 72$ strain gauges are retrieved in Table 10.

The median strain in the flanges (plates without any edge preparation) is observed to be 43 % to 56 % larger than in the web (plates with edge preparation and single-bevel butt welds) depending on the width-to-thickness ratio (Fig. 11a). Additionally, the ratio of minimum residual strains in the flange and web, i.e., maximum compressive strains dominating buckling problems, varies between 0.93 and 1.28. For single-pass welds, corresponding to plate thicknesses of 4 mm and 6 mm ($B/t = 36.7$ and 50), the absolute value of the median strains in each constituent plate is within $60 \mu\text{m/m}$, while the extrema of medians are $-472 \mu\text{m/m}$ and $-303 \mu\text{m/m}$ in the flange and web, respectively for $B/t = 36.7$. However, this is not the case for $B/t = 25$, where double-pass welds are employed and a clear decreasing trend with increasing plate thickness is observed, aligning with the reduction in the relative area of the fusion zone compared to the base material. In addition, subsequent weld passes (i.e., 2nd weld pass in this case) has a stress-relieving effect on previous weld passes (i.e., 1st weld pass here). Consequently, a smaller

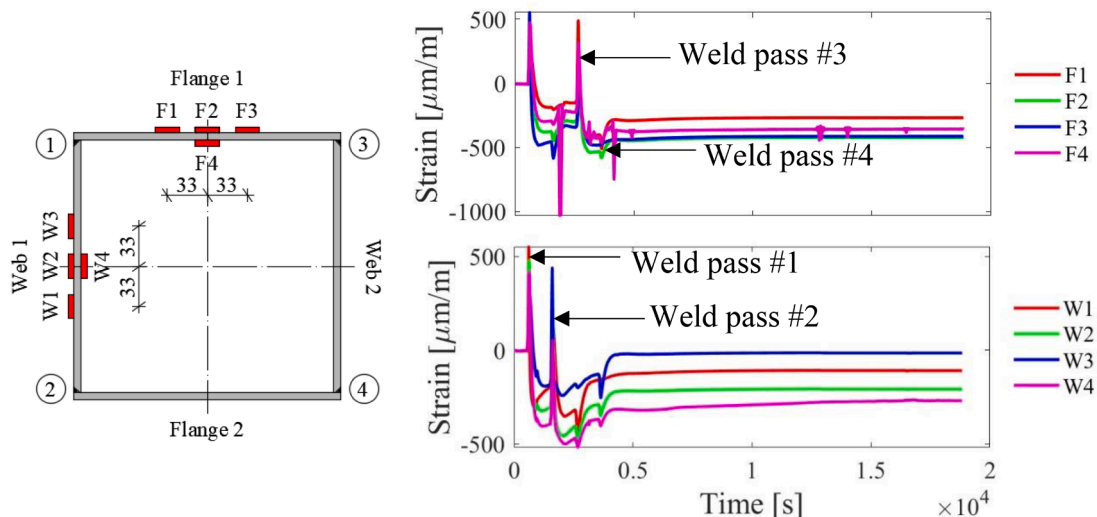
relative shrinkage force is induced by welding for plate thickness of 8 mm which needs to be in equilibrium with the resultant force of compressive stresses. This finding supports the theory of reduced shrinkage forces for multi-pass welds, as discussed in [51].

From a different perspective, median strain in the flanges is 59 % to 78 % larger than in the webs when considering different steel grades (Fig. 11b). Nevertheless, maximum compressive strains are 11 % to 45 % larger in the flanges for the various steel grade configurations. It is quite notable that medians are within $25 \mu\text{m/m}$ for HSS and hybrid specimens. In hybrid box sections, flanges are from normal strength steel (S355MC) and webs are from high strength steel (S700MC). On the other hand, NSS specimens exhibit substantially higher welding-induced compressive strains. Median strains are $-518 \mu\text{m/m}$ and $-291 \mu\text{m/m}$ representing increases of up to 35 % and 29 % in the flange and web, respectively, compared to the strains observed in HSS and hybrid box sections. It can be explained by underscoring that the same filler material was used for all the specimens which means an overmatching filler in the case of NSS sections. This generates a larger shrinkage force compared to a matching filler metal, which consequently increases compressive strains and stresses far from the weld.

Since external and internal strain gauges are installed on both the flange and web, magnitude of longitudinal membrane strains $\epsilon_{m,z,\text{centre}}$ is deduced by averaging the measured residual strains at the same location at the centre of constituent plates. Different quantities are created for representing a specific feature in accordance with welding-induced shrinkage force and residual stresses (Fig. 12). First, membrane strains are evaluated considering the effect of both net heat input q and the measured cross-sectional area of weld metal A_w (Table 8). The quantity $q \cdot A_w$ is assumed to be somehow proportional with the compressive membrane strains since it represents the simplified model of a shrinkage tendon force in the tensile zone, while internal equilibrium is the

Table 9Welding-induced residual axial strains [$\mu\text{m/m}$] at each strain gauge.

Specimen	F1	F2	F3	F4	W1	W2	W3	W4
RS4-700A	-395	-603	-571	-434	-236	-395	-200	-369
RS4-700B	-351	-429	-404	-420	-90	-358	-150	-321
RS4-H	-360	-382	-431	-384	-195	-423	-60	-393
RS6-355	-400	-555	-545	-490	-241	-340	-147	-402
RS6-700	-441	-514	-406	-390	-222	-292	-313	-318
RS6-H	-305	-468	-475	-485	-167	-410	-241	-435
RS8-700A	-249	-350	-319	-516	-123	-207	-380	-196
RS8-700B	-225	-354	-307	-334	-288	-266	-231	-133
RS8-H	-304	-299	-304	-473	-299	-211	-205	-201

**Fig. 9.** Position of strain gauges and measured strains during welding and cooling of specimen RS6-355.

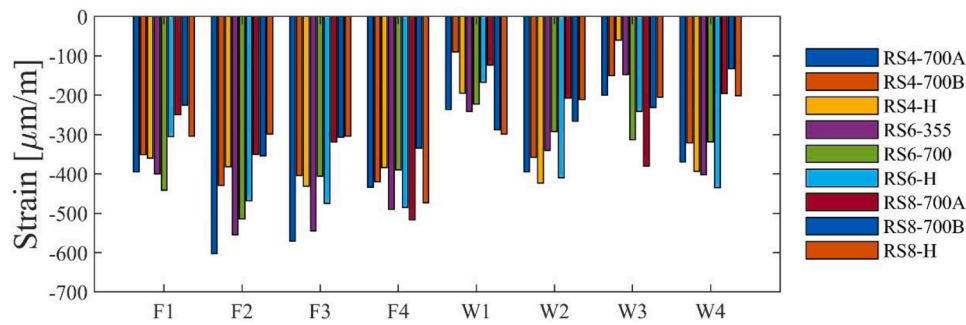


Fig. 10. Grouping of welding-induced residual axial strains.

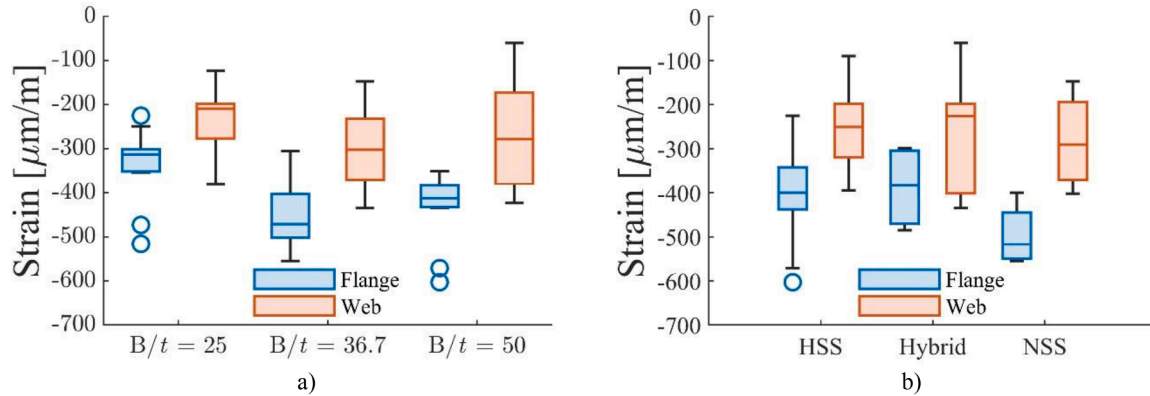
Fig. 11. Box charts of residual strains: for a) width-to-thickness ratio B/t and b) different steel grades (outliers are indicated by circles).

Table 10

Statistical data of welding-induced strains [$\mu\text{m/m}$] (*outliers are not included).

Metrics	$B/t = 25$		$B/t = 36.7$		$B/t = 50$		HSS		Hybrid		NSS	
	Flange	Web	Flange	Web	Flange	Web	Flange	Web	Flange	Web	Flange	Web
Maximum*	-249	-123	-305	-147	-351	-60	-225	-90	-299	-60	-400	-147
Upper quartile	-302	-199	-403	-232	-383	-173	-342	-198	-305	-198	-445	-194
Median	-313	-209	-472	-303	-412	-288	-400	-251	-383	-226	-518	-291
Lower quartile	-352	-277	-502	-371	-433	-381	-342	-320	-471	-402	-550	-371
Minimum*	-354	-380	-555	-435	-434	-423	-571	-395	-485	-435	-555	-402

requirement of residual stresses. It is in accordance with the shrinkage force model in the book of Olsson [51], which assumes that $P = C \cdot A_w$, where P is the longitudinal shrinkage tendon force due to welding, C is a factor considering the welding process, while A_w is cross-sectional area of the weld. In the case of double-pass welds (i.e., RS8 specimen group), mean heat input of the two weld passes is taken into account in accordance with A_w for the entire welded joint based on macrographs. A slight decrease in compressive membrane strains is emerging for larger values of $q \cdot A_w$. Secondly, the trend with different $1/t$ values is plotted since it was used as a variable in different residual stress models proposed for box-sections [22,35,36]. A clear increase in compressive membrane strains can be observed for larger values of $1/t$ (up to 105 % in the web). Thirdly, $1/t$ is transformed to $1/(B \cdot t)$ for normalization purposes since different section widths, $B = 200$ mm and 220 mm, are used. On the other hand, $B \cdot t$ is somewhat proportional with the area of the compressive zone since the width of the tensile zone is typically described as a function of t . Finally, the quantities above are merged, and the $q \cdot A_w / (B \cdot t)$ values are calculated representing the shrinkage force distributed over the contributing area of one weld, i.e., one quarter of the box section. Regression lines for the data points are calculated using the least squares method. The Mean Absolute Percentage Error (MAPE) is used as the measure of goodness-of-fit for the regression analysis,

yielding values of 9 % and 24 % for the flange and web, respectively; thus, scatter in the case of plates with edge preparation is larger. Overall, $q \cdot A_w / (B \cdot t)$ effectively merges the effect of different primary variables on welding-induced membrane strains in welded box-sections. It needs to be underscored that the effect of yield strength is not considered in this metric since the same filler material is used in all the specimens which tend to dominate the magnitude of shrinkage force.

Contour method used for evaluating residual stresses, including the influence of hot-rolling, thermal cutting, welding, etc., in the welded box-sections, is described in detail in the Section 3.6 as a dominant part of the current paper. It makes it possible to distinguish between solely welding-induced strains or stresses and residual stresses due to all the manufacturing processes.

3.5. Shape measurements

Geometrical imperfection of each constituent plate is measured after welding using a special mobile device with a linear variable differential transformer (LVDT). The instrument, driven by an electric motor, moves along a beam track of a rectangular hollow section fixed at both ends. Actual longitudinal position of the device and vertical displacement are registered simultaneously during the measurement at a sampling rate of

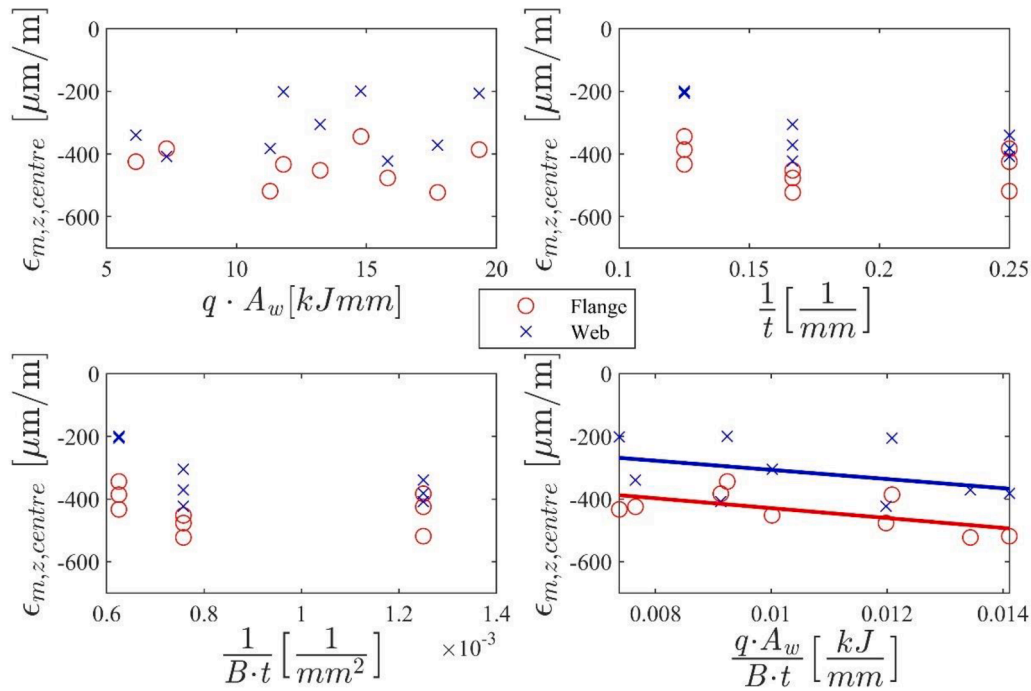


Fig. 12. Welding-induced longitudinal membrane strains plotted versus different quantities.

50 Hz. An outline of the experimental setup is shown in Fig. 13. The deformed shape is created for evaluating local imperfections (out-of-flatness) and global imperfections (bow imperfection/straightness) by using multiple measurements in both transverse and longitudinal direction. Measurements are taken along five longitudinal (uniformly distributed on each plate) and two transverse paths (one at each end) on the constituent plates. First and fifth longitudinal paths are located adjacent to the weld toes on the webs, resulting in a reduced measurement width, whereas the entire width is measured for the flanges. Measured data for each path are adjusted at intersections of the measurement paths for assembling surface data, while displacements are zeroed out at the corners (thus, any twisting in the surface is neglected). Posterior evaluation of data is carried out in MATLAB. Thin-plate smoothing spline, a special case of a polyharmonic spline, is used in the software to interpolate surfaces over scattered data and smoothing; therefore, all geometrical imperfections can be visualized simultaneously without distinguishing between local and global imperfections (Fig. 14a). The name of the spline-based algorithm refers to the physical analogy of bending energy of a thin sheet on point constraints. Measured imperfections at longitudinal edges are zeroed out and corrections are made on imperfections of internal points accordingly (deducting

linearly varying imperfections between the edges) for determining only out-of-flatness results (Fig. 14b) without global effects (Fig. 14c). Magnitudes of local out-of-flatness (Δ_{local}) and global imperfection (Δ_{global}), i.e., bow imperfection, are summarized in Table 11. Out-of-flatness varies between 0.28 mm and 0.86 mm, while bow imperfection is between 0.44 mm and 1.33 mm. Normalized imperfections are also presented in the table for each specimen. Normalization is based on the essential tolerance for plate curvature (local imperfection) with a permitted deviation of $\Delta_{\text{local,tol}} = B/200$ if $B/t \leq 80$ of Classes 1 and 2, and essential tolerance of $\Delta_{\text{global,tol}} = L/1000$ for straightness (global imperfection). Normalized values for local imperfections range from 0.25 to 0.86, while for global imperfections the range is from 0.56 to 1.66. Consequently, local imperfections are within the tolerances outlined in EN 1090-2. It can also be deduced that the maximum out-of-flatness, approximately $B/230$ (for specimen RS4-700B), closely aligns with the equivalent geometric imperfection for panels and subpanels ($B/200$) recommended by EN 1993-1-5, which is supposed to take into account both geometrical imperfections and residual stresses. Thus, modification of local equivalent geometric imperfection for panels in welded box sections is requisite. The maximum normalized local imperfections are 0.44, 0.73, and 0.86 for NSS, HSS, and hybrid cross-

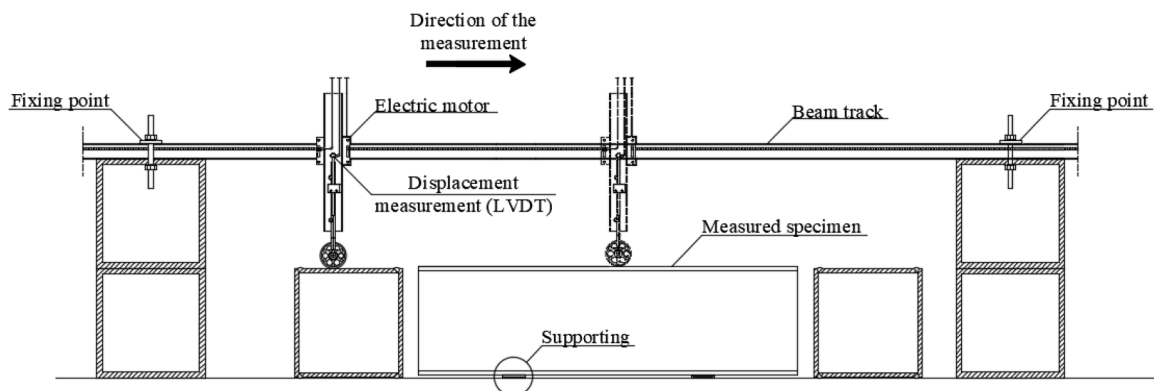


Fig. 13. Sketch for the shape measurement set-up.

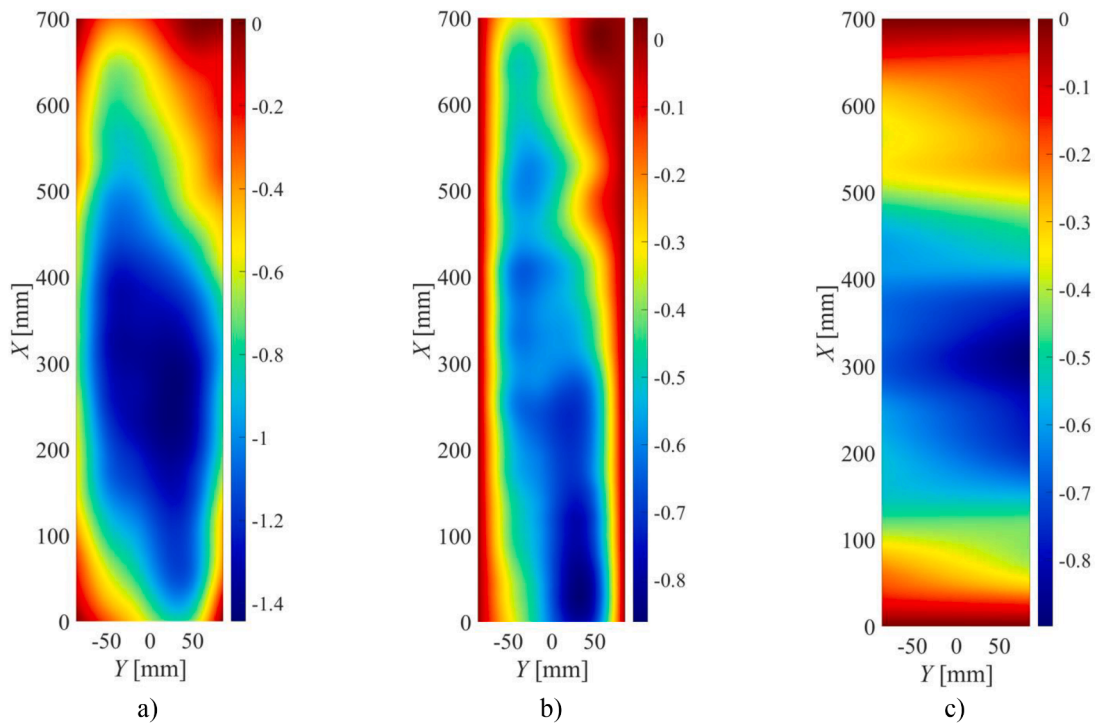


Fig. 14. Results of distortion measurements: a) measured shape of a web plate, b) local and c) global imperfections for specimen RS4-700B

Table 11

Measured local and global imperfections related to EN 1090-2 tolerances.

Specimen	L [mm]	B [mm]	Δ_{local} [mm]	Δ_{global} [mm]	$\Delta_{\text{local}}/\Delta_{\text{local,tol}}$ [-]	$\Delta_{\text{global}}/\Delta_{\text{global,tol}}$ [-]
RS4-700A	700	200	0.29	0.91	0.29	1.30
RS4-700B	700	200	0.86	0.90	0.86	1.29
RS4-H	700	200	0.33	1.01	0.33	1.44
RS6-355	800	220	0.48	1.33	0.44	1.66
RS6-700	800	220	0.28	0.44	0.25	0.56
RS6-H	800	220	0.80	0.98	0.73	1.23
RS8-700A	700	200	0.37	1.11	0.37	1.59
RS8-700B	700	200	0.48	0.75	0.48	1.07
RS8-H	700	200	0.32	0.44	0.32	0.63

sections, respectively, indicating a transitional behaviour between NSS and HSS, particularly at the local imperfection level, in the case of hybrid box sections. Notably, the hybrid solution proves to be more cost-effective than HSS. Conversely, global bow imperfections surpass the EN 1090-2 limit in seven specimens. The maximum normalized global imperfections are 1.66, 1.44, and 1.59 for NSS, HSS, and hybrid cross-sections, respectively. It is emphasized that the measured imperfections encompass not only the impact of welding but also the influence of the initial shape of plates (out-of-flatness) and assembly with tack welds.

3.6. Contour method

Two-dimensional full-map residual stress measurements are conducted after manufacturing using the so-called contour method, a variation of Bueckner's superposition principle [52] proposed by Prime [53]. This principle assumes the material retains elastic behaviour during residual stress relaxation and material removal process introduces negligible stresses affecting measured displacements. The contour method is a destructive technique offering notable precision compared to alternative residual stress measurement methods. Kollár et al. [54] reported that mean standard deviation is 22–34 MPa when using contour method for assessing residual stresses in orthotropic steel

decks, which is comparable with other measurement techniques, e.g., neutron and X-ray diffraction techniques (20–40 MPa) [55,56] or hole-drilling technique (about 40 MPa with several hundred MPa in near surface measurements) [57].

The residual stress distribution can be determined using contour method in a specific cross-section after cutting the specimen into two parts. Initially, the specimen encompasses undisturbed residual stresses (Step A: $\sigma_A(x, y, z)$), reflecting the equilibrium of internal forces and bending moments in the specimen (Fig. 15a). This includes the cumulative effect of manufacturing processes such as hot-rolling, thermal cutting, assembling, welding, etc. Subsequently, the specimen is cut into two parts (Fig. 15b), leading to the release of residual stresses and elastic deformation perpendicular to the cutting surface. Wire electric discharge machining (WEDM) is employed for cutting (Fig. 16a), utilizing a non-contact technique with negligible residual stresses induced by spark erosion during material removal. This study employs brass wire with a diameter of 150 μm and a cutting speed of 0.08 mm/s, while specimens are clamped during the operation. After cutting and releasing residual stresses, the surface is in a plane stress state (Step B: $\sigma_B(x, y, z)$), resulting in deformations. A coordinate measuring machine (CMM), specifically a moving bridge-type Zeiss UMC 850 (Fig. 16b), is utilized with a scanning probe head and a measurement range of 1200 mm $\times$ 850 mm $\times$ 600 mm to measure the three-dimensional distorted surfaces. The CMM uses a ruby stylus with a diameter of 6 mm, ensuring measurement accuracy within 6 μm with a resolution of 0.1 μm . Temperature effects are minimized by conducting measurements in a temperature-controlled metrology laboratory with air temperature of 20–20.5 $^{\circ}\text{C}$. The scanning route is determined based on the premeasured outline of each cross-section, accounting for offsets of 0.5 mm (Fig. 17a) to avoid uncertainties near the edges due to cut quality and measurement details according to Schajer [57]. These data at the edges cannot be used directly in the evaluation process; the trimmed points are shown in Fig. 17b. The practical limitation of the contour method lies in the requirement for constituent plates to have a thickness of at least 3–4 mm. Thus, it is a well-suited approach for the analysed welded box-sections with a minimum thickness of 4 mm. The measurement is conducted with varying point densities, with a 0.2 mm average distance

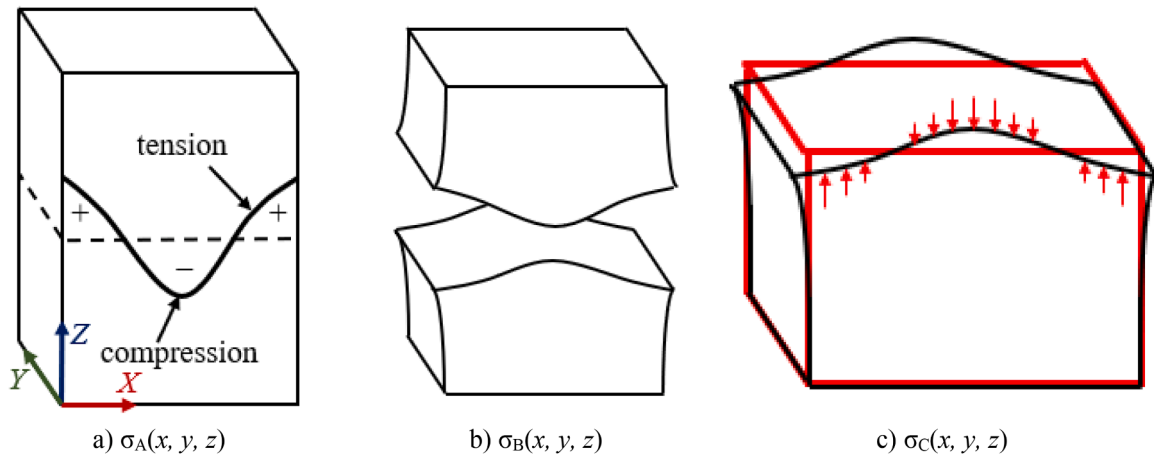


Fig. 15. Background of contour method: a) initial residual stress state, b) deformed shape after cutting (elastic spring-back) and c) forcing deformed surface back to original shape [54].

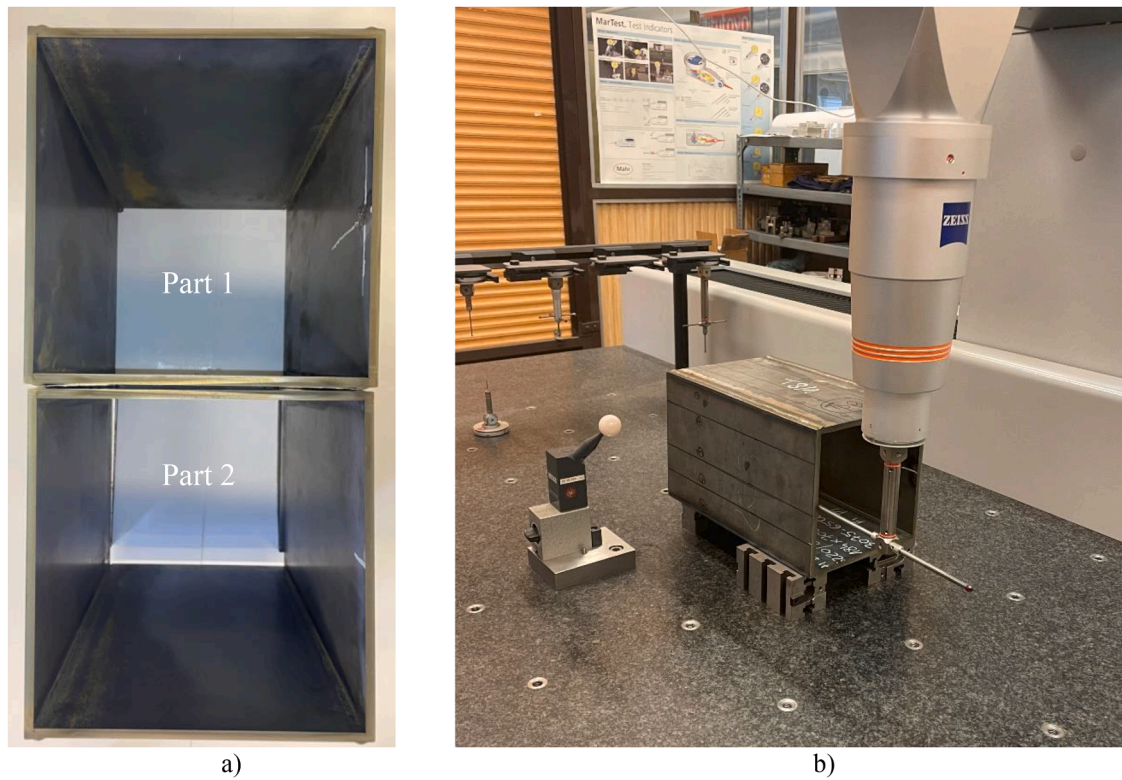


Fig. 16: a). Surfaces after WEDM cutting, and b) CMM measurement with Zeiss UMC 850.

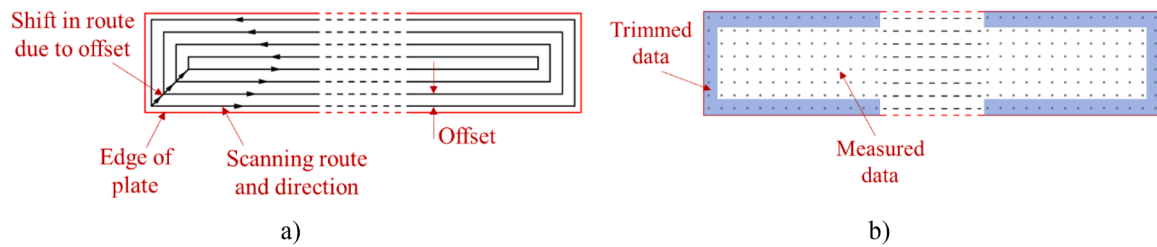


Fig. 17. Scheme of a) CMM scanning route with offset, and b) data trimming at the edges of a flange [54].

between points near the weld and 0.5 mm in further regions. Bueckner's superposition principle, based on linear elasticity, necessitates forcing the measured deformed surface back to its original shape (Fig. 15c) after WEDM cut and elastic spring-back (Step C: $\sigma_C(x, y, z)$). This allows the evaluation of the residual stress distribution, induced by all manufacturing steps, in the original specimen by using $\sigma_A(x, y, z) = \sigma_B(x, y, z) + \sigma_C(x, y, z)$. Although the method provides a high-resolution, two-dimensional residual stress field, it is limited to measuring relatively small specimens due to size constraints imposed by CMM and WEDM. The approach has not been used for box sections, yet which implies a novel adaptation in this paper.

CMM measurements are carried out on both cutting surfaces (left and right side of cutting). Posterior evaluation of data is carried out in MATLAB [50]; details are described in [54] including data trimming at the edges, averaging of contour data on the two halves, and removal of measurement noise by data smoothing using thin-plate smoothing spline. Surfaces after smoothing for all the nine specimens are shown in Fig. 18. In the figure, the same scale is used for visual comparison of different configurations; minimum and maximum measured

out-of-plane displacements vary between -170 and 70 μm .

Then, the specimens are modelled in detail in ANSYS [58], a general-purpose finite element software, using 8-node solid elements (SOLID185 with enhanced strain element technology and pure displacement element formulation) with linear shape functions. The measured cross-sectional geometries with the actual plate thicknesses, corner angles, weld bead shapes, etc. are modelled for easier point cloud mapping and precise evaluation of residual stresses. Linear isotropic material model, small deflection theory, and initially flat cutting surface is used for the inverse linear elastic finite element analysis for modelling elastic spring-back. Young's modulus E is assumed to be 210,000 MPa for NSS and HSS constituent plates, while Poisson's ratio ν is 0.3. It needs to be underscored that nominal values for E and ν are used in the numerical model assuming a spatially uniform microstructure and material properties for each constituent plate. It is important to emphasize the utilization of nominal values for E and ν in the numerical model, assuming a spatially uniform microstructure and material properties for each constituent plate. The Joint Committee on Structural Safety (JCSS) reports a coefficient of variation for E of 0.03. The nominal Young's

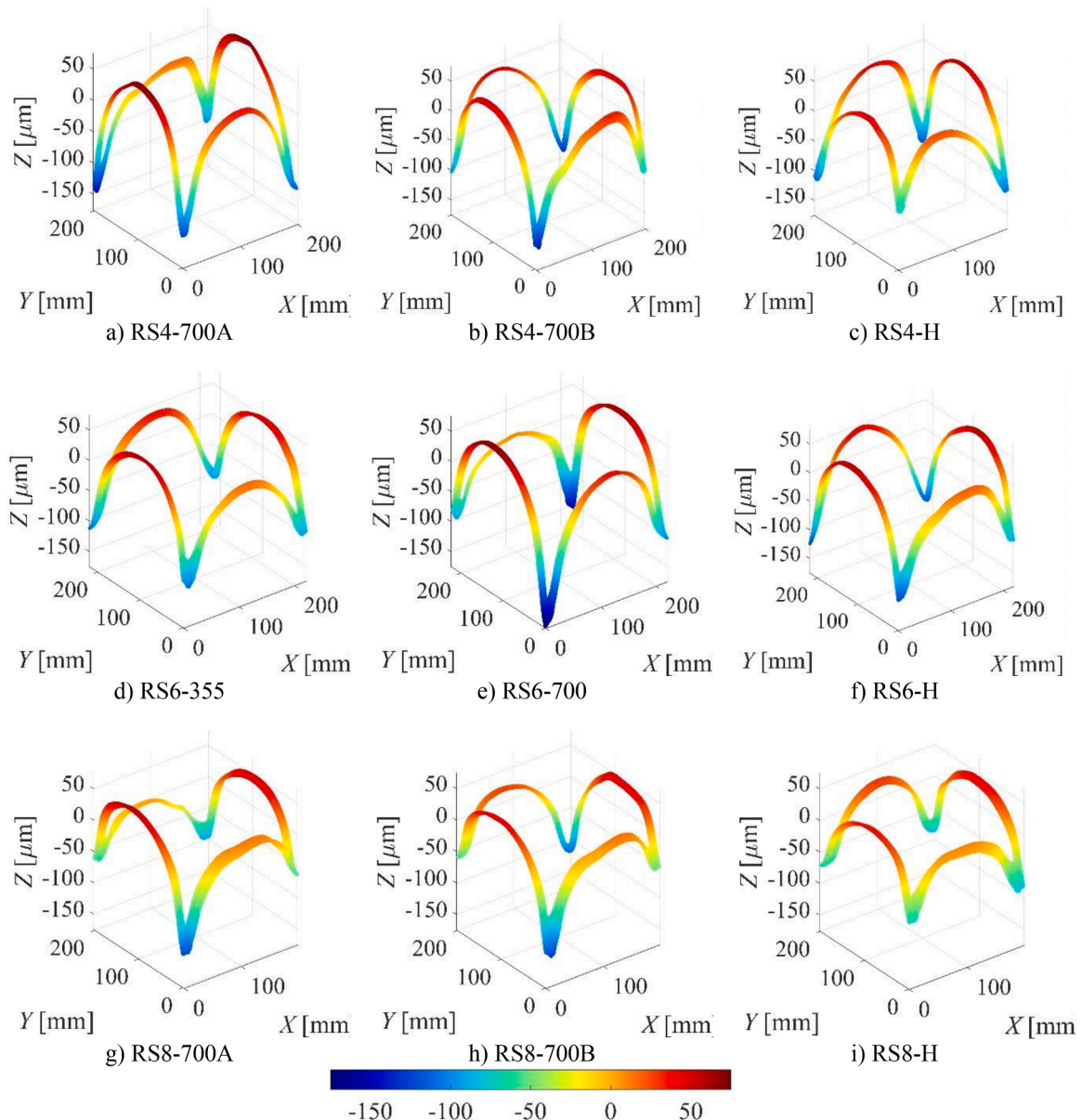


Fig. 18. Point clouds after postprocessing raw data. Units are in μm .

modulus ranges from 200,000 to 210,000 MPa for martensite, bainite, and ferrite/pearlite. While the base material has a ferritic-pearlitic microstructure for S355MC and a ferritic-bainitic microstructure for S700MC, small variations in Young's modulus may also occur due to phase transformations near welds. However, these effects are considered negligible on a macroscale in the development of a residual stress model and are disregarded in the analysis, similarly to other techniques such as in the case of the hole-drilling method in general. Lengths of the models are equivalent to half of the total specimen length, which is 350 mm or 400 mm accordingly. Average mesh size of $e_{cs} = 1$ mm is applied in the cross-section, incorporating a nonuniform mesh with 20 elements in the axial direction and a spacing ratio of 50 between the first and last finite element lengths. This results in a finer mesh near the cutting surface. Smoothed measurement data (Fig. 18) are then incorporated into the three-dimensional finite element model using superimposed displacements in the opposite direction, enabling the determination of the full two-dimensional residual stress distribution across the cutting surface. The *MOPER, MAP command in the software is employed for mapping measured displacements from the set of points to the finite element mesh. Fig. 19a shows the deformed finite element model (scaling factor is 25) and additional boundary conditions to prevent rigid body motion are denoted as well in the figure. Fig. 19b presents longitudinal residual stresses on the entire model with isometric view. It is represented that residual stresses decrease gradually as solid elements and nodes are further from the cutting surface with imposed displacements. Mesh sensitivity analysis is carried out, regarding $\sigma_{rs,z,t,max}$ maximum longitudinal tensile and $\sigma_{rs,z,c,max}$ compressive residual stresses, in order to verify the applied mesh scheme (Table 12). Quantities Δ_t and Δ_c denote percentage error or tensile and compressive stresses, respectively compared to the case with average mesh size of $e_{cs} = 1$ mm.

Longitudinal residual stresses ($\sigma_{rs,z}$) arising from various manufacturing processes such as thermal cutting, edge preparation, assembly, and welding, etc. are analysed for all specimens. Finite element analysis results, detailed in Fig. 20, reveal prominent peaks of high tensile longitudinal residual stresses near the welds. These stress peaks can locally approach the nominal yield strength of the base material, resulting in extreme stress gradients and a highly nonlinear residual stress profile in the affected region. Typically, substantial compressive stresses are observed at greater distances from the weld beads. The compressive stress in the middle of the constituent plates is about $\sim 0.10\text{--}0.24f_y$ (or $\sim 0.10\text{--}0.24f_{p0.2}$, considering the nominal strength values). The evaluated local approximate compressive stresses

Table 12

Results of mesh sensitivity analysis of specimen RS6-700.

e_{cs} [mm]	Number of nodes [-]	Number of elements [-]	$\sigma_{rs,z,t,max}$ [MPa]	$\sigma_{rs,z,c,max}$ [MPa]	Δ_t [%]	Δ_c [%]
1	145,656	121,380	782.5	-211.3	0	0
2	50,757	39,540	771.8	-208.7	-1.4	-1.2
3	27,930	20,680	753.9	-205.4	-3.7	-2.8
4	18,816	13,400	710.3	-200.3	-9.2	-5.2
5	13,188	8960	720.5	-231.0	-7.9	9.3

vary between $\sim 95\text{--}145$ MPa, $\sim 85\text{--}100$ MPa, and $65\text{--}85$ MPa for plate thickness of 4 mm, 6 mm and 8 mm. There is a clear decreasing trend with increasing plate thickness, which corresponds to the reduced relative area of the fusion zone compared to the base material. This observation aligns with the theory of reduced shrinkage forces in multi-pass weld specimens as discussed earlier in Section 3.4.

Results exported from ANSYS are further analyzed in MATLAB to assess residual stresses. The full-map longitudinal residual stresses in a representative cross-section are used to determine longitudinal membrane residual stresses ($\sigma_{rs,m,z}$), helping to clarify stress patterns in welded box sections. These membrane residual stresses can also serve as residual stress patterns for shell element models in design. Membrane residual stresses, which are the average stresses through the thickness t , are calculated using Eq. 2. However, due to the complexity at web-to-flange joints, where geometry changes occur due to weld bead shape, an alternative method is used. Internal longitudinal forces ($\sum F_{i,z}$) in the vicinity of these joints are summed and then divided by the corresponding junction area (A_{joint}) to obtain the average residual stresses at the corners. This approach is necessary because averaging through the thickness is not straightforward in regions with geometric changes (as shown in Fig. 21). Numerical calculations for determining membrane residual stresses are performed in MATLAB, utilizing local x (along perimeter) and y (through thickness) coordinates for each constituent plate.

$$\sigma_{rs,m,z}(x) = \frac{1}{t} \int_{-t/2}^{t/2} \sigma_{rs,z}(x, y) dy \quad (2)$$

The determined longitudinal membrane residual stress distributions for the flange and web plates are shown in Fig. 22 in the case of specimen RS4-H as an example. The figure clearly shows the expected tendencies for the weldments. Positive (+) sign indicates tensile stresses at the

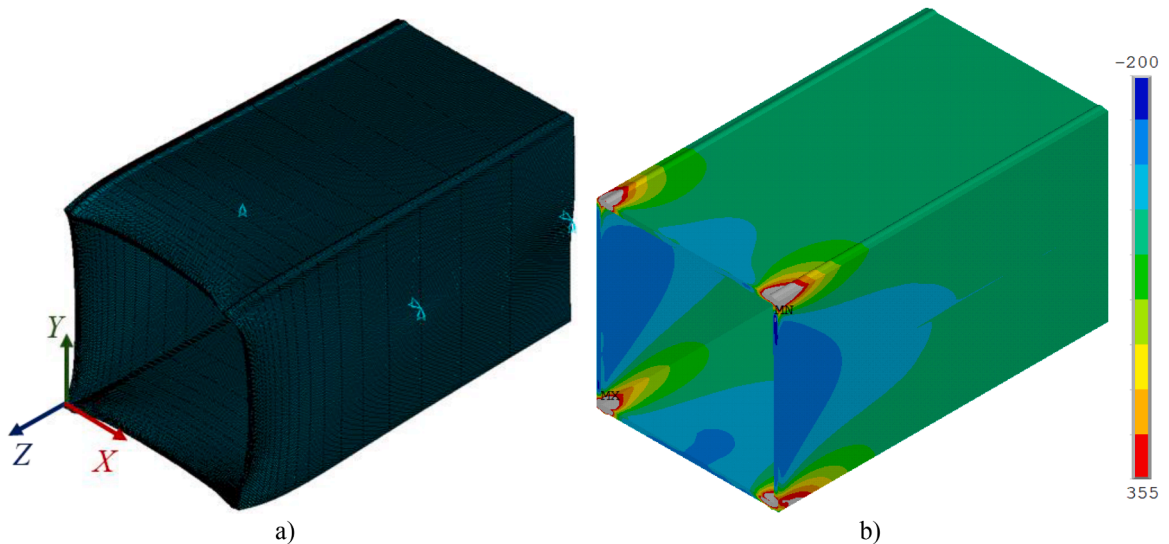


Fig. 19: a). Finite element mesh with scaled displacements (scaling factor is 25) and additional boundary conditions to prevent rigid body motion, b) overview of longitudinal residual stresses [MPa] in the model.



Fig. 20. Longitudinal residual stresses ($\sigma_{rs,z}$) in [MPa] for all nine specimens.

corners (near local coordinates $x = 0$ and $x = 200$ mm), negative (-) sign denotes compressive stresses in the farther regions. High tensile stress peaks and relatively large gradients are observed near the weld beads. In this particular hybrid specimen, the flanges are made from steel grade S355MC, and the web plates are S700MC. Maximum tensile stress is 543 MPa in the flange, exceeding the yield strength of the base material; however, it is less than the yield strength of the applied overmatching filler material. In addition, hardening of the material near the weld metal also affects the magnitude of residual stresses. On the other hand, maximum compressive stress is 129 MPa in the flange which is $\sim 0.32f_y$ (considering $f_y = 402$ MPa based on the inspection certificate of the base material with thickness of 4 mm). The measured maximum compressive stress is in a good agreement with the prediction of Kövesdi and Somodi [22]; their proposed formula in Table 2 gives 128 MPa with $t = 4$ mm and $B = 200$ mm.

The conventional longitudinal membrane residual stress versus local coordinate plots are evaluated for all the specimens. Since residual stresses need to satisfy the requirement of internal equilibrium, the correctness and goodness of the contour measurements are verified by determining the unbalanced sectional residual stresses $\sigma_{unbalanced}$ for the entire cross-section using Eq. 3:

$$\sigma_{unbalanced} = \frac{\sum \sigma_{rs,m,z,i} \cdot \Delta_i}{L_p} \quad (3)$$

where $\sigma_{rs,m,z,i}$ is the membrane residual stress at each point, Δ_i is the contributing width of each stress point, while L_p is the perimeter along the neutral planes of constituent plates (shown in Fig. 21 with dashed lines). Fig. 23 presents the obtained unbalanced sectional residual stresses using the contour method. Unbalanced sectional residual stresses range only from -27.5 MPa to -1.4 MPa, which meet the requirement of equilibrium of residual stresses in general. Moreover, 27.5 MPa is only 3.7 % of the proof strength for specimen RS4-700A (considering $f_{p0.2} = 746$ MPa for S700MC based on the inspection certificate of the base material with thickness of 4 mm).

Maximum and minimum tensile and compressive membrane residual stresses are determined as well (Fig. 24) for all the specimens in both the denoted flanges and web plates. Tensile membrane stress peaks ($\sigma_{rt,max}$) still vary between 292 MPa (RS8-H with hybrid cross-section) and 600 MPa (RS6-700 with HSS plates). It is crucial to note that membrane residual stresses generally do not exceed the yield strength of the base material, although localized regions surpassing the nominal yield strength are evident, as shown in Fig. 20. By concentrating on membrane

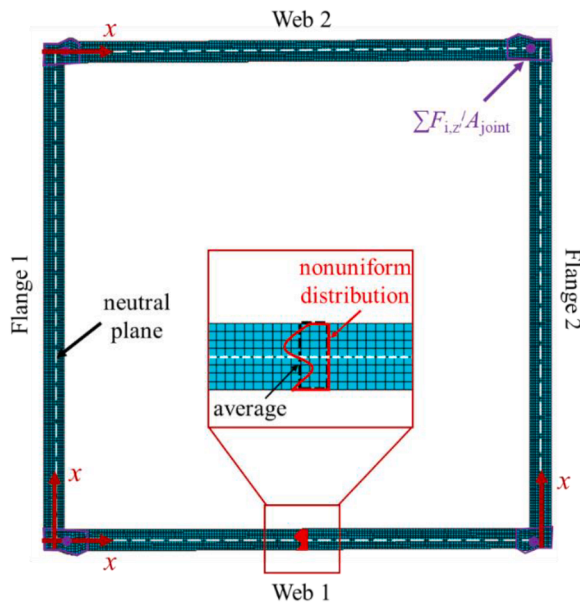


Fig. 21. Demonstration of membrane residual stress calculation based on finite element model using solid elements.

stresses, the local peaks in the 2D full-map residual stress fields are effectively filtered out, aligning well with the findings of Schaper et al. [59]. Similarly, lower tensile membrane residual stresses are observed near welds in welded I-sections, which can be attributed to high stress gradients and a decrease in through-thickness stresses. Scatter of data is characterized by the tensile stress ranges. On the one hand, range of maximum tensile stresses is ± 19 MPa for RS4-700A with constituent plates made of HSS. On the other hand, as another extremum, it is ± 75 MPa for the hybrid cross-section RS4-H with NSS and HSS plates unambiguously representing a large influence of applying different steel grades within one cross-section. Moreover, compressive stress extrema ($\sigma_{rc,max}$) are between 40 MPa and 175 MPa showing a larger scatter even within one specimen.

Membrane stresses are evaluated as well in the middle of the constituent plates, where transient strain gauge measurements are also carried out during welding. It makes it possible to assess the amount of residual stresses in welded box-sections due to pre-welding manufacturing processes such as thermomechanical rolling of plates,

thermal cutting, edge preparation and assembly. Since longitudinal membrane strains $\epsilon_{m,z,centre}$ are deduced in Section 3.4 by averaging the measured residual strains at the same strain gauge locations, and it is shown in Section 3.2 that the uniaxial stress assumption applies based on the dimensional analysis, welding-induced longitudinal membrane residual stresses $\sigma_{m,z,wrs,centre}$ at the centre of constituent plates can be estimated using Eq. 4 assuming 2D plane stress state:

$$\sigma_{m,z,wrs,centre} = \frac{E}{1-\nu^2} (\epsilon_{m,z,centre} + \nu \epsilon_{m,x,centre}) \quad (4)$$

where E is Young's modulus, ν is Poisson's ratio, while $\epsilon_{m,z,centre}$ and $\epsilon_{m,x,centre}$ are longitudinal and transverse membrane strains. Young's modulus E is assumed to be 210,000 MPa for both NSS and HSS constituent plates, while Poisson's ratio ν is 0.3 for all the specimens. Since the uniaxial stress assumption applies, $\epsilon_{m,x,centre}$ is zeroed out. Membrane stresses at the same location based on strain gauge measurements (influence of welding only), and the contour method (effect of entire manufacturing process) are shown in Fig. 25. Additionally, the difference Δ between the two conditions is calculated, revealing that pre-welding manufacturing steps lead to a variation of compressive membrane stresses ranging from -32 MPa to +36 MPa, which is approximately $\sim 0.05\text{--}0.10f_y$.

4. Development of residual stress model

Finally, a novel residual stress model is developed for welded box sections with single-bevel butt welds. The previous contour method-based membrane residual stresses in the flange and web plates makes

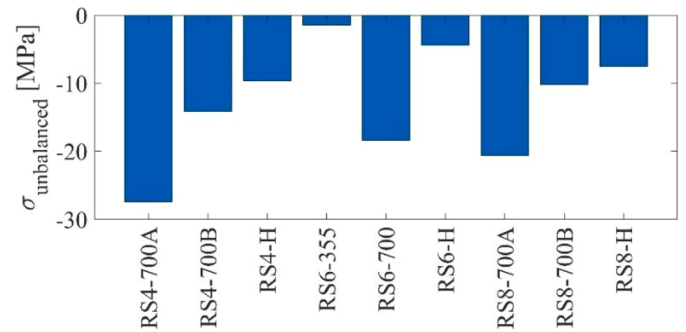


Fig. 23. Internal equilibrium of residual stresses in the welded box-sections.

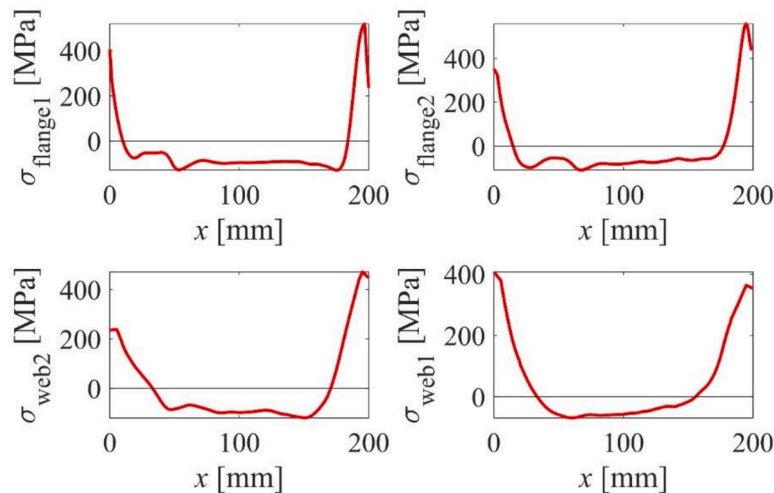


Fig. 22. Longitudinal membrane residual stresses in the flange and web plates for specimen RS4-H. Positive (+) sign indicates tensile, negative (-) sign denotes compressive stresses.

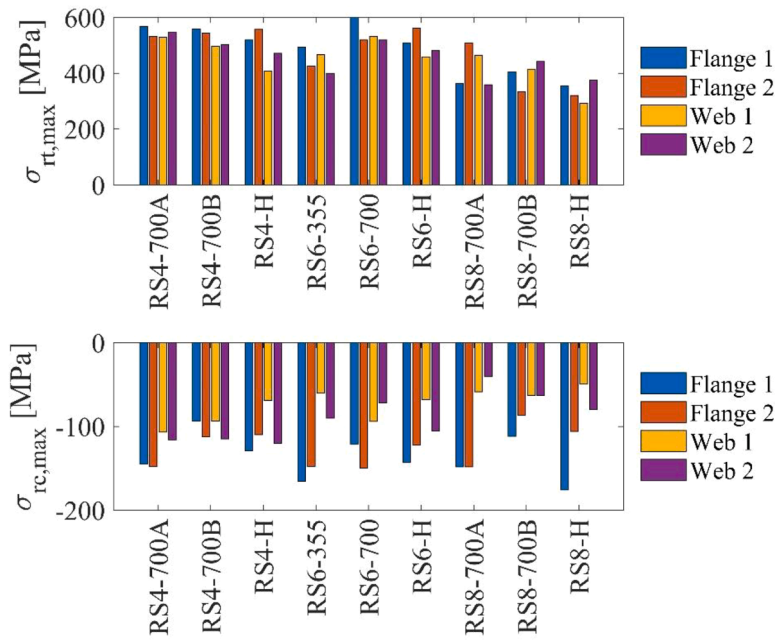


Fig. 24. Maximum tensile and compressive membrane stresses in flanges and web plates.

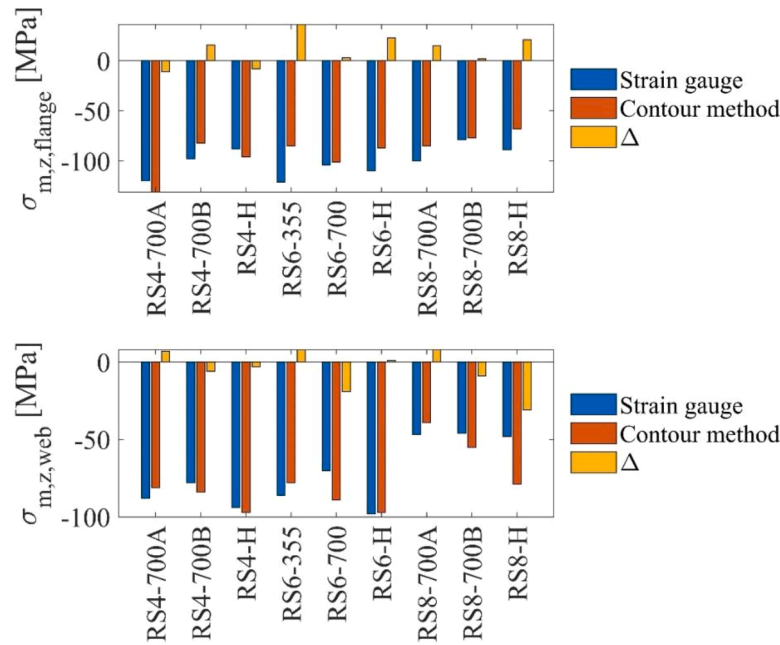


Fig. 25. Difference (Δ) of membrane stresses at the centre of flange and web plates due to welding ('Strain gauges') and the entire manufacturing process ('Contour method').

is possible to determine the primary variables of an advanced residual stress model. Shape of the residual stress model (Fig. 26) is identical to Model 1 recommended by ECCS [1] and BSK 99 [38]; thus, trapezoidal shapes are used for describing the simplified residual stress distribution in NSS, HSS and hybrid box sections. Novelty of the model is based on (i) the consideration of welding technology parameters and (ii) its applicability for hybrid sections.

Primary variables are evaluated for the analysed specimens based on membrane stress distributions. The following steps are carried out:

- 1) Tensile residual stress σ_{rt} is assessed by averaging maximum measured tensile stresses in the corners.
- 2) Width of tensile stress plateau α_{1t} is derived from the evaluated membrane stress distributions. Eight values are calculated for the four constituent plates; then, these values are averaged for each specimen.
- 3) Width of tensile stress block α_{2t} is derived similarly as α_{1t} ; however, the intersection points of the measured membrane stress curves and $\sigma = 0$ are evaluated.
- 4) Relationship between welding technology parameters and residual stress model parameters is established.

$$\alpha_1 = 1.0$$

$$\alpha_2 = -0.3224 \times qA_{w,nom} + 5.6908 \quad (5)$$

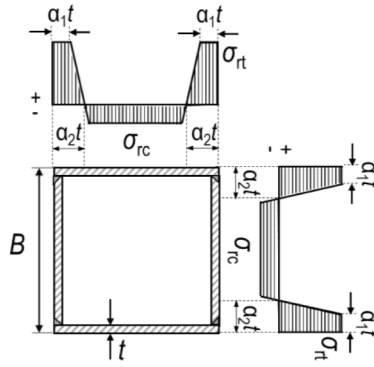


Fig. 26. Novel residual stress model for welded box sections.

$$\varepsilon_{rs} = \sqrt{\frac{400}{\max(f_{y,filler}, f_{y,fl}, f_{y,w})}} \quad (6)$$

$$\sigma_{rt} = \varepsilon_{rs} \cdot \max(f_{y,filler}, f_{y,fl}, f_{y,w}) \cdot n_{wpass}^{-2/3} \quad (7)$$

σ_{rc} based on equilibrium

Fig. 26 summarizes the residual stress model parameters. After linear regression analysis, α_1 is considered to be 1.0 (Fig. 28a), while a clear relationship (Eq. 5) between α_2 and $qA_{w,nom}$ is determined (Fig. 28b), where $q = \eta UI/v$ is heat input [kJ/mm] (the mean heat input is used for multi-pass welds) and $A_{w,nom}$ is the nominal total cross-sectional area of a single-bevel butt weld seam [mm²]. Similarly to the residual stress model for welded I-sections proposed by Schaper et al. [59], steel grade is considered in the magnitude of tensile residual stress σ_{rt} by a modified yield strength $f_y \cdot \varepsilon$, where material coefficient of the base material is $\varepsilon = (235/f_y)^{1/2}$. However, the model proposed by Schaper et al. solely considers the yield strength of the base material and is not developed for hybrid sections. In contrast, the residual stress model presented in this paper incorporates the effect of steel grades of both web ($f_{y,w}$) and flange ($f_{y,fl}$) plates, while the influence of filler material ($f_{y,filler}$) is also covered with the modified material coefficient ε_{rs} (Eq. 6). On the one hand, it makes the model suitable for hybrid sections and allows for assessing the influence of overmatching filler material. On the other hand, lower tensile membrane stresses are considered in the vicinity of the welds which is explained with the high gradients, decrease of through-thickness stresses and the reduced shrinkage forces for multi-pass welds by Olsson [51]. The latter effect is considered by using the factor $n_{wpass}^{-2/3}$ (Eq. 7), according to Olsson [51] and Clarin [60], where n_{wpass} is the number of weld passes in a weld seam. It is emphasized that weld type significantly influences both the extent of the fusion zone, heat-affected zone and the region affected by the initial yield temperature [44], where plastic strains evolve (Fig. 27), due to edge preparation

$$\alpha_1 = 1.0$$

$$\alpha_2 = -0.3224 \times qA_{w,nom} + 5.6908 \quad (5)$$

$$\varepsilon_{rs} = \sqrt{\frac{400}{\max(f_{y,filler}, f_{y,fl}, f_{y,w})}} \quad (6)$$

$$\sigma_{rt} = \varepsilon_{rs} \cdot \max(f_{y,filler}, f_{y,fl}, f_{y,w}) \cdot n_{wpass}^{-2/3} \quad (7)$$

σ_{rc} based on equilibrium

and required heat input. Consequently, width of tensile residual stress zone, denoted as $\alpha_1 t$ and $\alpha_2 t$ in the proposed model, is directly affected by the weld type. This dependency thus introduces a limitation to the proposed residual stress model. While tensile residual stresses magnitude is mainly governed by the yield strength of constituents and weld passes, the tensile zone width is primarily influenced by welding variables (namely heat input as denoted in Eq. 5). Since the compressive residual stress σ_{rc} is derived based on equilibrium of internal forces, its magnitude increases with the tensile residual stress zone width.

The measured and predicted residual stresses, both tensile and compressive, are shown in Fig. 28c and d. The mean absolute error is 29.7 MPa and 7.6 MPa for tensile and compressive residual stresses, respectively. Primary variables and predicted model parameters are summarized in Table 13; in addition, mean measured membrane tensile and compressive stresses are also shown for comparison.

Residual stresses are also predicted using different available residual stress models, described and summarized in Section 2, which are available in the international literature. The residual stress models of ECCS [1] (both for light and heavy welds), the Swedish standard BSK 99 [38], the Chinese code [39], Kövesdi & Somodi [22], Ban et al. [35], and Khan et al. [36] are applied; nevertheless, it needs to be highlighted these are not specifically developed for hybrid sections. Applicability of the listed models is uncertain for the box sections analysed in this study, since their validity range (criteria detailed in Table 2) may fall outside the parameter set analysed in the current paper. Nevertheless, only two models, namely BSK 99 and the model proposed by Kövesdi and Somodi, satisfy all the criteria related to parameters such as thickness, width-to-thickness ratio, yield strength, joint and weld types for all the nine specimens. However, neither these models address the hybrid configuration of box sections. Comparison of measured tensile and compressive residual stresses with predictions using the different residual stress models is summarized in Table 14. Errors of the aforementioned models, including the residual stress model proposed in this paper, are plotted in Fig. 29 using box charts for tensile and compressive residual stresses σ_{rt} and σ_{rc} , respectively. Median, lower and upper quartiles, any outliers (applying $1.5 \times$ interquartile range as a reference

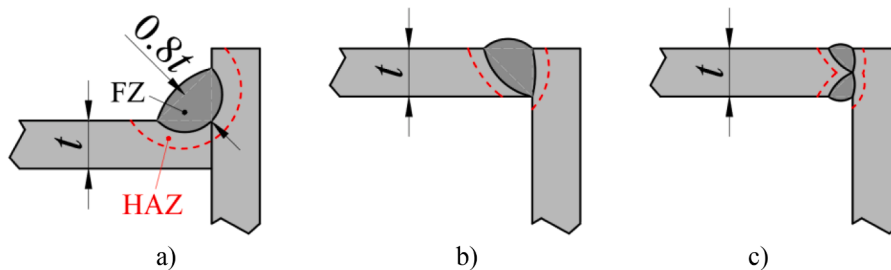


Fig. 27. Schematic of fusion zone (FZ) and heat-affected zone (HAZ) size for a) fillet weld (throat thickness is 0.8t), b) single-bevel butt weld and c) double-bevel butt weld (bevel angle is 45°).

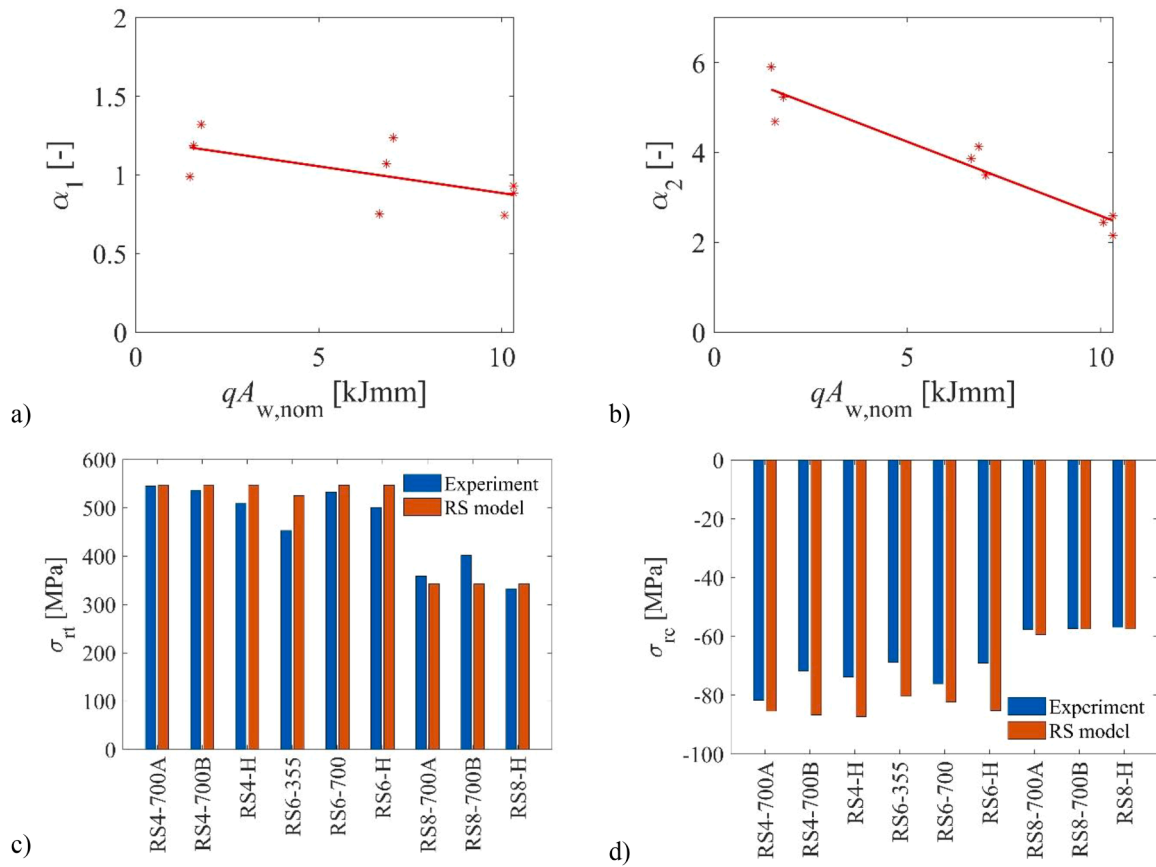


Fig. 28. Mean model parameters a) α_1 and b) α_2 versus $qA_{w,nom}$ and the fitted model parameters (denoted with red continuous line); c) mean tensile and d) compressive residual stresses ('Experiment') versus predicted values ('RS model').

Table 13

Predicted ('model') and measured ('mean') residual stresses.

Specimen	B [mm]	t [mm]	n_{wpass} [-]	$qA_{w,nom}$ [kJmm]	$f_{y,fl}$ [MPa]	$f_{y,w}$ [MPa]	$f_{y,filler}$ [MPa]	$\sigma_{rt,model}$ [MPa]	$\sigma_{rt,mean}$ [MPa]	$\sigma_{rc,model}$ [MPa]	$\sigma_{rc,mean}$ [MPa]
RS4-700A	200	4	1	1.79	746	746	690	546.3	544.9	-85.4	-81.7
RS4-700B	200	4	1	1.58	746	746	690	546.3	535.6	-86.7	-71.7
RS4-H	200	4	1	1.47	746	402	690	546.3	510.1	-87.3	-73.8
RS6-355	220	6	1	6.84	466	466	690	525.4	453.0	-80.4	-68.7
RS6-700	220	6	1	7.03	749	749	690	547.4	533.2	-82.2	-76.0
RS6-H	220	6	1	6.66	749	446	690	547.4	500.9	-85.2	-69.1
RS8-700A	200	8	2	10.08	738	738	690	342.3	359.1	-59.3	-57.6
RS8-700B	200	8	2	10.32	738	738	690	342.3	402.0	-57.4	-57.3
RS8-H	200	8	2	10.32	738	400	690	342.3	332.5	-57.4	-56.9

in Matlab [50]), and the minimum and maximum values (that are not outliers) are plotted. These statistical data are based on a total of 9×8 error values based on measurement results for both compressive and tensile residual stress magnitudes. The developed model shows a mean error (μ) of 2.3 % and 10.7 % for tensile and compressive stress magnitudes with standard deviation (s) of errors of 8.2 % and 8.6 %, respectively. The residual stress model in the Swedish code demonstrates relatively good performance, with mean errors and standard deviations ranging from 3.2 % to 18.8 % and 18.8 % to 57.9 %, respectively, though it still underperforms compared to the proposed model. In contrast, other models exhibit mean errors exceeding 58 % for both tensile and compressive stresses. In addition, the Chinese code and the ECCS model for heavy welds show mean errors of hundreds of percent for compressive stresses.

5. Conclusions

A comprehensive experimental work is carried out focusing on NSS (S355MC), HSS (S700MC) and hybrid (combination of NSS and HSS) box sections with single-bevel butt welds. The measurements reveal the following key findings:

- A novel residual stress model is proposed for welded box sections with single-bevel butt welds which is applicable for NSS, HSS and hybrid sections. The model considers manufacturing technology parameters such as heat input, cross-sectional area of weld seam, number of weld passes, yield strength of filler material and steel grades of constituent plates. The developed model shows a mean error (μ) of 2.3 % and 10.7 % for tensile and compressive stress magnitudes with standard deviation (s) of errors of 8.2 % and 8.6 %, respectively outperforming available residual stress models in the literature.

Table 14

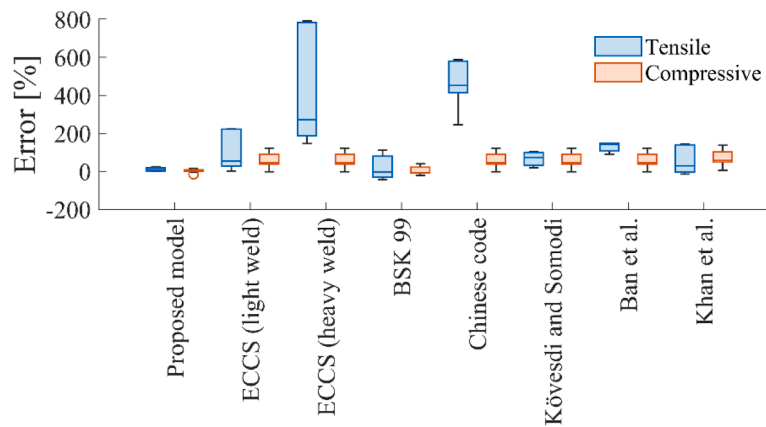
Comparison of measured ('mean') tensile (σ_{rt}) and compressive (σ_{rc}) residual stresses [MPa] with predictions using different residual stress models. Mean (μ) and standard deviation (s) of errors based on measurements are summarized as well.

Specimen			RS4-700A	RS4-700B	RS4-H	RS6-355	RS6-700	RS6-H	RS8-700A	RS8-700B	RS8-H	Errors [%]	
												μ	s
Measurement	σ_{rt}		544.9	535.6	510.1	453.0	533.2	500.9	359.1	402.0	332.5	–	–
	σ_{rc}		-81.7	-71.7	-73.8	-68.7	-76.0	-69.1	-57.6	-57.3	-56.9	–	–
Proposed model	σ_{rt}		546.3	546.3	546.3	525.4	547.4	547.4	342.3	342.3	342.3	2.3	8.2
	σ_{rc}		-85.4	-86.7	-87.3	-80.4	-82.2	-85.2	-59.3	-57.4	-57.4	10.7	8.6
ECCS [1] (light weld)	σ_{rt}		746.0	746.0	746.0	446.0	749.0	749.0	738.0	738.0	738.0	58.0	36.3
	σ_{rc}		-97.0	-97.0	-97.0	-69.9	-117.3	-117.3	-184.5	-184.5	-184.5	97.5	90.0
ECCS [1] (heavy weld)	σ_{rt}		746.0	746.0	746.0	446.0	749.0	749.0	738.0	738.0	738.0	58.0	36.3
	σ_{rc}		-216.3	-216.3	-216.3	-168.7	-283.4	-283.4	-507.4	-507.4	-507.4	405.1	273.5
BSK 99 [38]	σ_{rt}		500.0	500.0	402.0	446.0	500.0	446.0	500.0	500.0	400.0	3.2	18.8
	σ_{rc}		-51.3	-51.3	-41.3	-65.9	-73.9	-65.9	-120.7	-120.7	-96.6	18.8	57.9
Chinese code [39]	σ_{rt}		746.0	746.0	746.0	446.0	749.0	749.0	738.0	738.0	738.0	58.0	36.3
	σ_{rc}		-395.4	-395.4	-395.4	-236.4	-397.0	-397.0	-391.1	-391.1	-391.1	462.3	105.4
Kövesdi and Somodi [22]	σ_{rt}		746.0	746.0	746.0	446.0	749.0	749.0	738.0	738.0	738.0	58.0	36.3
	σ_{rc}		-128.0	-128.0	-128.0	-91.2	-91.2	-91.2	-115.2	-115.2	-115.2	66.3	30.5
Ban et al. [35]	σ_{rt}		746.0	746.0	746.0	446.0	749.0	749.0	738.0	738.0	738.0	58.0	36.3
	σ_{rc}		-178.1	-178.1	-178.1	-143.7	-143.7	-143.7	-141.3	-141.3	-141.3	128.2	21.1
Khan et al. [36]	σ_{rt}		798.2	798.2	798.2	477.2	801.4	801.4	789.7	789.7	789.7	69.1	38.8
	σ_{rc}		-73.5	-73.5	-73.5	-58.5	-98.3	-98.3	-138.0	-138.0	-138.0	52.4	64.9

Note 1) Interpolation is carried out for B/t in the case of σ_{rc} for the ECCS models.

Note 2) $B/t = 40$ is used for the specimens with $B/t > 40$ in the case of ECCS models.

Note 3) σ_{rc} is set as $\min(f_{y,\Omega}, f_{y,w}, 500 \text{ MPa})$ in the case of BSK 99 model.

**Fig. 29.** Comparison of different residual stress models.

- Essential tolerance-based (based on EN 1090-2) normalized local (out-of-flatness) and global (bow) imperfections range from 0.25 to 0.86, and 0.56 to 1.66, respectively. Maximum out-of-flatness is approximately $B/230$ closely aligning with the equivalent geometric imperfection for panels and subpanels ($B/200$) recommended by EN 1993-1-5. Modification of local equivalent geometric imperfection for panels in welded box sections is recommended, which needs further investigations.
- Manufacturing-induced compressive stress in the middle of the constituent plates varies between ~ 95 – 145 MPa, ~ 85 – 100 MPa, and 65 – 85 MPa for plate thickness of 4 mm, 6 mm and 8 mm (~ 0.10 – $0.24f_y$). A clear decreasing trend with increasing plate thickness is shown, which corresponds to the reduced relative area of the fusion zone compared to the base material.
- Dimensional analysis and the calculated Rosenthal numbers, along with the corresponding aspect ratios based on the liquidus temperature, indicate that fast MAG welding heat sources are used in the analysed nine specimens. This supports the validity of assuming uniaxial residual stresses as a simplification.
- The theory of reduced shrinkage forces for multi-pass welds is supported by the measurements for specimens with a thickness of 8 mm where double-pass welds are applied.
- Contour method is used for evaluating two-dimensional longitudinal residual stress fields due to the entire manufacturing process. The approach has not been used for box sections, yet which implies a novel adaptation in this paper.
- Ratio of maximum welding-induced compressive strains in the flange and web varies between 0.93 and 1.28 for different width-to-thickness ratios, while maximum compressive strains are 11 % to 45 % larger in the flanges for the various steel grade configurations.
- Difference between welding-induced and manufacturing-induced membrane residual stresses is evaluated at the centre of constituent plates. It is revealed that pre-welding manufacturing steps lead to a variation of compressive membrane residual stresses ranging from -32 MPa to $+36$ MPa, which is approximately ~ 0.05 – $0.10f_y$.

The future work focuses on refining the parameters of the proposed residual stress model using validated manufacturing simulations. For instance, the influence of combining additional structural steel grades, both NSS (S235-S355) and HSS (S420-S960), width and thickness, and number of weld passes (e.g., dozens of weld passes for heavy welds used especially in bridge engineering) need to be investigated.

CRediT authorship contribution statement

A. Horváth: Writing – original draft, Visualization, Software, Investigation, Formal analysis, Data curation. **D. Kollár:** Writing – original draft, Visualization, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **B. Kövesdi:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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