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Column Stability during Welding

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Abstract. This research is part of the project of strengthening of steel members under load using plates welded parallel to the member axis. Buckling load resistance of columns has to be checked during welding under compressive load. A part of a cross-section is ineffective due to high temperature near the weld. The centre of gravity is shifted and the decisive cross-section is loaded by additional bending moment. Moreover, the weld causes deformations, which are higher than in case of regular welding. This paper presents authors' method determining the buckling load resistance of the compressed member during welding. The method takes into account the column cross-section, slenderness, and effective intensity of the welding heat source. The column is treated as a stepped member and its Euler's critical load is decreased. The deformation of the column and the stress are determined with regards to second order effects. The method is validated by experiments performed in the laboratory of Department of Metal and Timber Structures at Brno University of Technology in November 2017. Columns with cross-sections HEA 100 and SHS 100×5 with the length of 3 m were loaded by the maximal force determined using the analytical method and under this constant load, the weld bead was being laid from the bottom of the column to 15 cm above the mid-height. Then, still during welding, the force was gradually increased until the column failed via flexural buckling. Measured values of load resistance, deformations and temperatures are compared with the authors' analytical method. All six specimens resisted the maximum calculated load and failed at slightly higher loads.

1. Introduction

This research is part of a broader topic – strengthening of steel members under load [1, 2]. Strengthening means increasing in cross-section area, which can be achieved easily, cheaply, and fast by welding additional plates to base member. During the process of welding, an area close to the weld is affected by high temperatures. The weld metal and heat affected zone are in a molten state for a very short while and recrystallization occurs. Further areas are temporarily affected by high temperatures and mechanical properties of steel are deteriorated [3]. The cross-section of the member that is being strengthened is therefore temporarily weakened [4]. The residual stress and deformations are permanently introduced into the member. Welding to members subjected to compressive load causes higher permanent deformations than welding to unloaded member [5, 6, 7]. Due to weakened cross-section and higher deformations, it is necessary to check the load resistance of the base member [4, 7].

2. Methods

The authors' analytical method was developed to determine the load resistance of base member with weakened cross-section subjected to compressive force. The method was validated on experiments described in this paper.

2.1. Analytical method

The analytical method assumes cross-section reduced by a part where temperatures are higher than 500 °C. Temperature can be determined by various means: experimentally with thermocouples or thermochalks, using finite element model or analytically. The simplest and thus most commonly used is the theory of moving point source of heat by Rosenthal [10, 11].

Effective intensity of the welding heat source, q, can be determined by the following equation where η_a is welding effectivity [8, 9, 10], U is electric voltage, I is electric current, and v is welding speed:

$$q = \eta_{\mathrm{a}} \cdot \frac{U \cdot I}{v} \tag{1}$$

Using Rosenthal's equations, a distance r_{500} where the maximum temperature T_p = 500 °C is reached can be determined. In addition, the length of the reduced cross-section can be determined from the cooling time. The cooling time is also important to avoid brittle martensitic structures in the weld and heat affected zone. The recommended cooling time from 800 °C to 500 °C, $t_{8/5}$, is between 15 and 30 s [8, 10].

Another step is to determine the increased critical load N_{cr} of the base member with weakened cross-section. The member is treated as a stepped member with the weakened section at the most dangerous location (in case of simply supported column in the mid-height). Apart from increased slenderness of the member, the centre of gravity of the weakened part of cross-section is shifted and there is additional moment. Furthermore, this additional bending moment causes further deformation of the weakened member. The deformation of the weakened member in the process of welding is:

$$w_{\mathrm{temp}} = \frac{1}{1 - \frac{N_1}{N_{\mathrm{cr,e}}}} \cdot e_{\mathrm{temp}} + \Delta w + \frac{5}{48} \cdot \frac{N_1 \cdot \Delta w \cdot L^2}{E \cdot I_0} \tag{2}$$

Where N_1, e_{temp}, L, E, and I_0 are the preload, amplitude of initial imperfection of the base member, member length, Young's modulus of elasticity, and moment of inertia of the base member, respectively.

Using second order theory, we can determine normal stress, σ_x, in the most stressed threads. The normal stress, $\sigma_{x,1}$, under the preload, N_1, is:

$$\sigma_{x,1} = \frac{N_1}{A_{\mathrm{temp}}} + \frac{w_{\mathrm{temp}} \cdot N_1}{W_{\mathrm{el,temp}}} \leq f_{\mathrm{y}} \tag{3}$$

Where A_{temp}, $W_{el,temp}$, and f_y are the area of the weakened cross-section, elastic section modulus of the weakened cross-section, and yield strength, respectively.

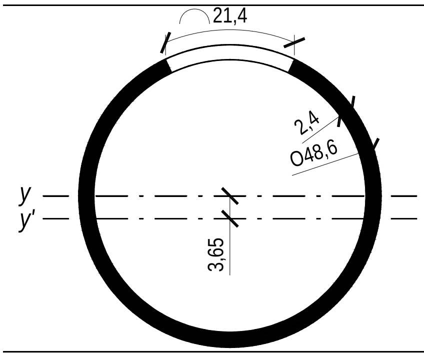
The yield strength should not be exceeded because yielding of a part of cross-section causes significant deformation and second order effects are increasing rapidly. The maximum possible preload is therefore found if $\sigma_{x,1}$ equals to f_y.

2.2. Experimental validation

The analytical method needs to be validated by experiments. From the literature, Suzuki's and Horikawa's experiments [7] were used. In addition, new experiments were performed at Brno University of Technology.

2.2.1. Experiments from literature. A gusset plate and a stiffener were being welded to CHS columns with the diameter of 48.6 mm and the thickness of 2.4 mm. Columns were simply supported and with the length of 1.6 m. The gusset plates were welded parallel to the column axis, the stiffeners were welded transversally across 1/3 of the column circumference. The overview of assumed properties of the base and weakened cross-sections is in table 1.

Table 1. Cross-sectional properties of the base member and assumed weakened part of member C-1-S



$A_0 =$	348	mm^2
$A_{temp} =$	300	mm^2
$I_0 =$	93 190	mm^4
$I_{temp} =$	64 703	mm^4
$W_{el,0} =$	3 835	mm^3
$W_{el,temp} =$	2 525	mm^3
$e_0 =$	2,72	mm
$e_{temp} =$	2,92	mm

The comparison of experimental results together with the analytical method is in table 2. The longitudinal welding of gusset plates (labelled C-1) is relatively safe while transverse welding of the stiffener (labelled C-2) should be avoided because a significant portion of the cross-section may be weakened.

Table 2. Experimental results compared to the analytical method; members, which failed during the welding, are underlined

Member	N_1 [kN]	α_g	w_{temp} [mm]	σ_x [MPa]	Δw_{temp} [mm]	w_0 [mm]	$\Delta w_{temp,exp}$ [mm]
C-1-H	28	0.45	10.06	$204 \leq 410$	2.10	7.52	1.2
C-1-S	35	0.57	11.51	$275 \leq 410$	2.81	8.23	2.1
<u>C-1-A</u>	<u>56</u>	<u>0.91</u>	<u>24.28</u>	<u>$722 > 410$</u>	<u>10.23</u>	<u>15.65</u>	
C-2-H	28	0.45	27.31	$1253 > 410$	9.07	15.37	4.0
<u>C-2-S</u>	<u>35</u>	<u>0.57</u>	<u>32.61</u>	<u>$1834 > 410$</u>	<u>13.63</u>	<u>19.94</u>	
<u>C-2-A</u>	<u>56</u>	<u>0.91</u>	<u>56.28</u>	<u>$3317 > 410$</u>	<u>34.55</u>	<u>40.45</u>	

The analytical method correctly predicted failure of all members during welding (C-1-H, C-1-S, C-2-S, and C-2-A) but also of member C-2-H, which did not fail. This might be caused by lower real amplitude of initial eccentricity and the fact that the weld was already cooler at the beginning of the weld and the smaller portion of the cross-section was weakened. The amplitude, w_0, includes the deformation due to weld shrinkage, Δ_{vert}, which was calculated according to Blodgett [13]. The value Δw_{temp} shows the difference between welding under load and under no load. The comparison with experimental values shows acceptable agreement.

2.2.2. Authors' experiments. Experiments were performed in November 2017 in the Laboratory of Institute of Metal and Timber Structures. The purpose of these experiments was to determine the maximum preload ratio, α_g, which is the ratio of preload magnitude, N_1, and base member resistance, $N_{b,0,Rd}$. Columns with cross-sections HEA 100 and SHS 100×5 with the length of 3 m were supported on knife edge bearings, i.e. pinned perpendicularly to weaker axis z. The columns were loaded to maximum preload ratio obtained from analytical method ($N_1 = 158$ kN, $\alpha_g = 0.79$ for HEA 100; $N_1 = 290$ kN, $\alpha_g = 0.85$ for SHS 100×5). Under this constant load, the weld bead was laid using gas metal arc welding shielded by carbon dioxide (see table 3, welding effectivity $\eta_a = 0.8$) from the bottom up to about 15 cm above the column mid-height. Then, still during welding, the force was increased until the column failed via flexural buckling. Horizontal deformation by draw-wire sensors (wu, wm1, wm2, wl) and vertical deformation by LVDT, axial force by loading cylinder and temperature in two heights using thermocouples (T1 – T7) were measured (see figures 1 and 2).

Table 3. Welding parameters and calculated cooling rate and distance to 500 °C isotherm

	I [A]	U [V]	v [mm/s]	q [J/mm]	T_0 [°C]	F_2	t_p [mm]	$\Delta t_{8/5}$ $^{(2D)}$ [s]	r_{500} [mm]
HEA	110	20.5	2.7	668	20	1	8	15.9	18.7
SHS	110	20.5	2.7	668	20	2	5	20.3	15.0

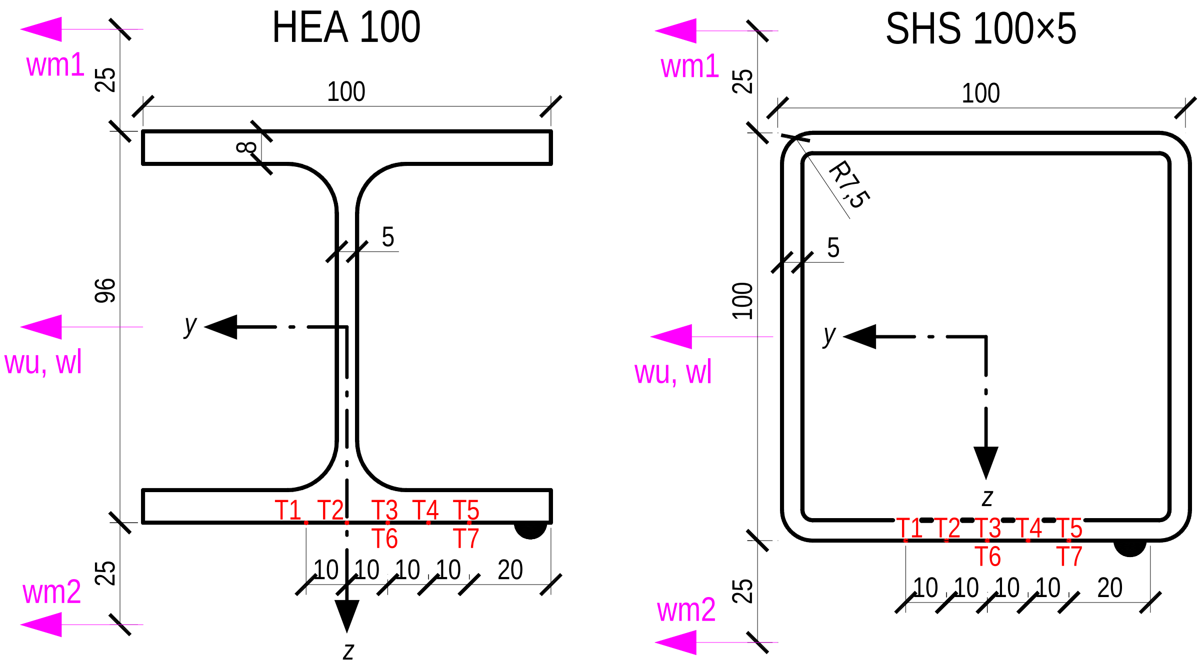


Figure 1. Cross-sections of specimens, positions of weld bead, thermocouples (T), and draw-wire sensors (w)

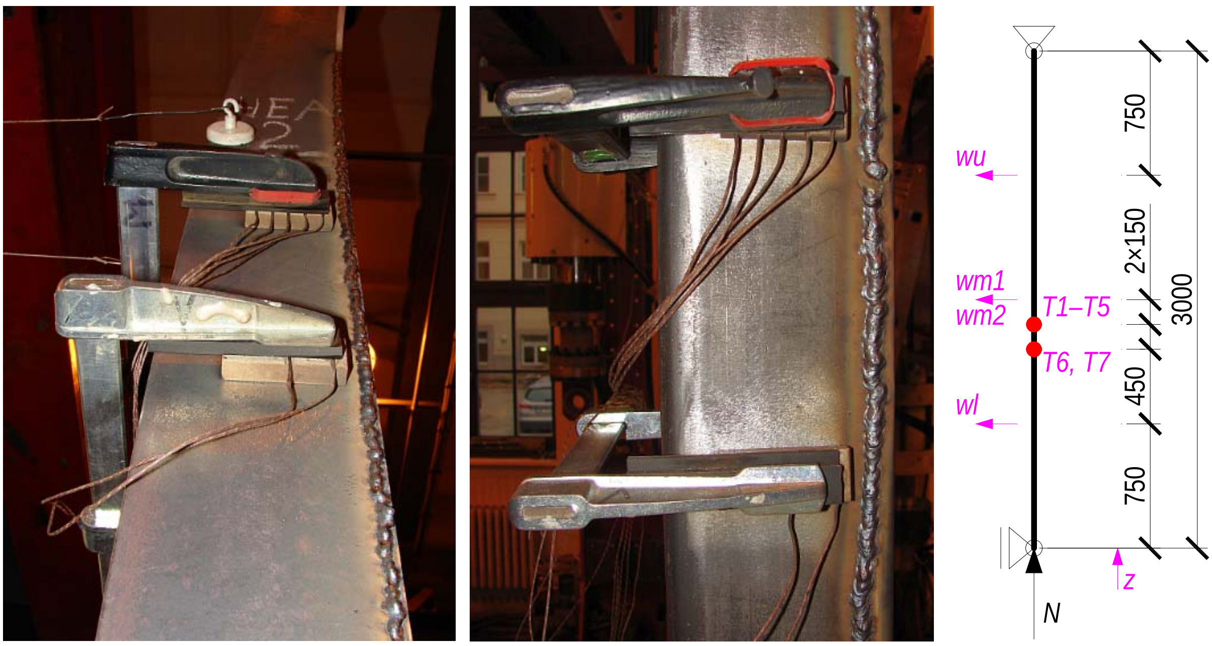


Figure 2. Placing of thermocouples via asbestos plates pressed by clamps on columns HEA2 and SHS1; scheme of measuring devices along the column height

3. Results and discussion

3.1. Temperature measurement

The graph of maximum temperature in dependence on distance from the axis of the weld bead is shown in figure 3. Experimental temperature measurement shows in all cases lower maximum temperatures than using Rosenthal's equations. Overall column temperature was affected by the weld very little. The temperature at the thermocouples increased by only 5 °C when the weld with the length of 1.1 m was performed. Then the temperature soared to about 350 °C at the distance of 15 mm from the weld axis (thermocouples T5 and T7). The dependence of temperature on time in various distances can be seen in the right graph in figure 3. The weld cools quickly and the temperature levels at all thermocouple positions. The failure of column HEA3 occurred at $t = 739$ s when the temperature on the closest thermocouple was 200 °C.

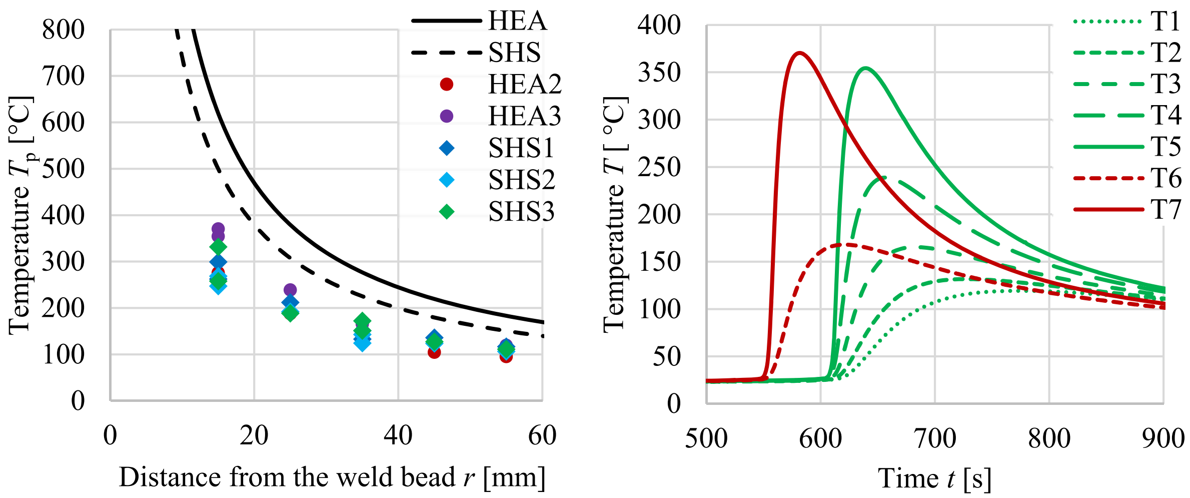
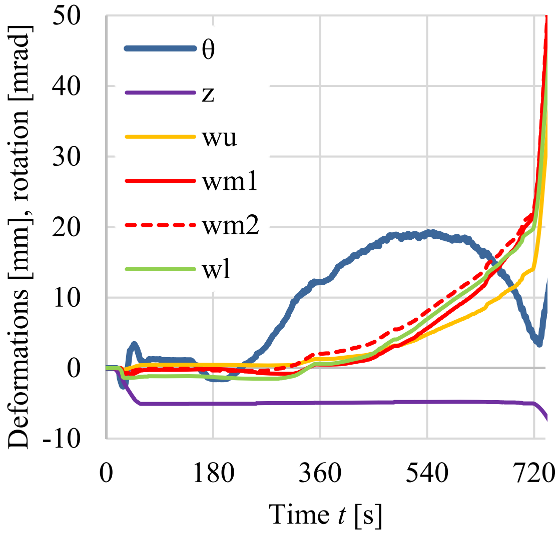


Figure 3. Results of temperature measurements on column HEA3

3.2. Deformation measurement

Deformations caused by welding and subsequent loading can be seen in figure 4. All tested columns failed by flexural buckling around the knife-edge bearing in the direction away from the weld. From the graph, especially on the right side of figure 4, the difference between deformation wu (in the upper quarter of the column) and wl (in the lower quarter of the column) can be seen. The weld bead was laid from the bottom of the column and caused a significant shrinkage. Open section columns HEA were also slightly rotated during welding but the rotation decreased during loading and flexural buckling. For this reason, it seems that torsional-flexural buckling does not have to be taken into account. Closed section columns SHS showed no rotation.

Comparison of analytical and experimental load resistance during welding is in figure 5. All tested columns resisted the maximum load calculated by analytical method and failed at slightly higher load during subsequent increase in the applied load. Columns HEA failed in average at load 191 kN (predicted elastic resistance 158 kN) and columns SHS failed in average at load 313 kN (predicted 290 kN). Considering use of nominal material characteristics of steel S235, the method might not be safe enough in this case of very long weld on one side of the column. Huenersen et al. [4] claim that during welding, the shrinkage caused by weld is not yet important. It seems, this is true only in case of short welds. The best way to avoid significant deformations from weld shrinkage is to plan welding sequence to avoid long welds and place them symmetrically on the cross-section. If this is not possible for some reason, e.g. unsymmetrical strengthening, the deformation caused by weld shrinkage, Δ_{vert}, should be taken into account in the equation (2) of the analytical method.



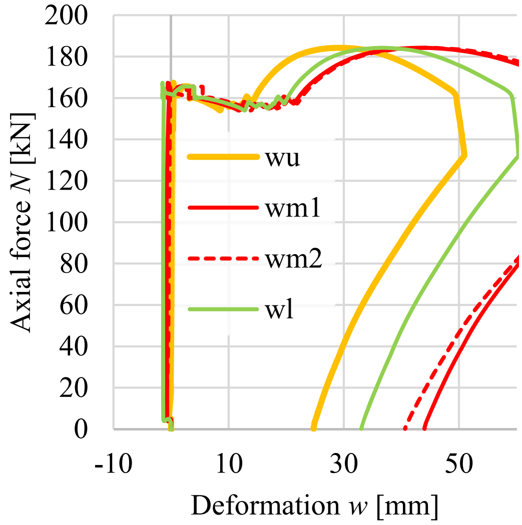


Figure 4. Column HEA3: Deformations in dependence on time and axial force

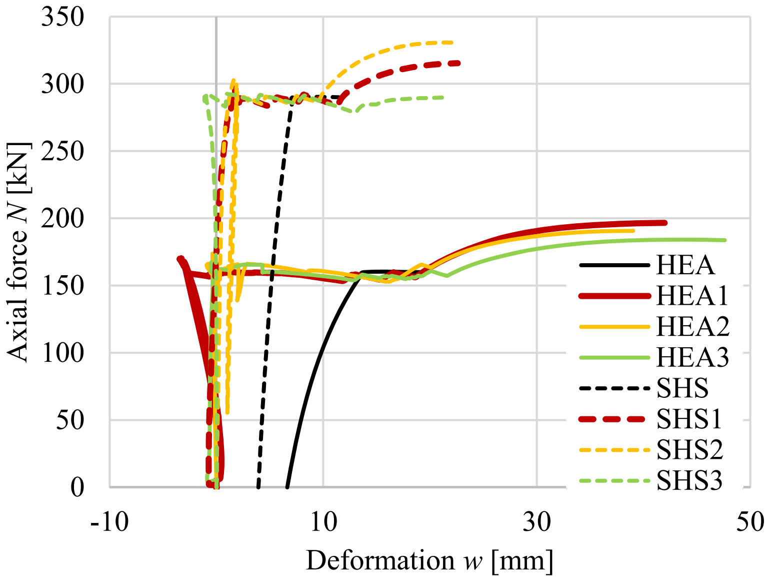


Figure 5. Failed column SHS1 with weld bead in the test set-up; deformations in the direction of axis y in mid-height (average of draw-wire sensors wm1 and wm2) in dependence on axial force compared to analytical method (black curves)

4. Conclusions

Welding under load parallel to a member longitudinal axis is feasible and does not influence the load resistance of the member significantly. The weld affects only a small area with high temperatures, which limit steel material properties. The buckling resistance is affected especially by increased deformation. The buckling resistance of slender columns is affected the most. Authors' analytical method was developed to determine the load resistance of the compressed member to which welding is performed. This method was designed using numerical simulations and validated by experiments presented in this paper. The method is based on determination of column deformation during welding and limiting the normal stress, calculated by including second order effects, to yield strength. If possible, the welding sequence should be designed to limit the deformation caused by weld shrinkage by dividing the weld into shorter segments and placing them symmetrically around the cross-section.

Experiments on open section members HEA 100 and closed section members SHS 100×5 were used to validate analytical method. All members failed, as expected, by flexural buckling in the direction away from the weld. The buckling resistance was 191 kN ($\alpha_g = 0.96$) and 313 kN ($\alpha_g = 0.91$) for HEA 100 and SHS 100×5, respectively. It is slightly higher than the resistance determined by analytical method. The use of analytical method instead of safe estimation can lead to material and time savings

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