

Strengthening under Load: Experimental and Numerical Research

M Vild^{1,2} and M Bajer¹

¹Brno University of Technology, Faculty of Civil Engineering, Institute of Metal and Timber Structures, Veveří 331/95, 602 00, Brno, The Czech Republic

E-mail: vild.m@fce.vutbr.cz

Abstract. The paper presents experimental and numerical research of strengthening of columns under load using welded plates. Three sets of three columns each were tested. All columns were 3 m long. The load from loading cylinders was transmitted through knife-edge bearings, which ensured pinned boundary condition perpendicular to the weaker axis. Set (A) comprised columns with welded T shaped cross-section. Set (B) comprised columns with welded monosymmetric I shaped cross-section. Both sets (A) and (B) had been loaded monotonically until collapse occurred. Set (C) contained columns with T shaped cross-section with the same dimensions as the columns in set (A). The columns from set (C) were first loaded to 70 kN. The force was being held constant and the second flange was being welded to the web under load. After the welding process was finished and the specimen cooled, the column was loaded to failure. The average forces at collapse of column sets (A), (B) and (C) were 143kN, 308 kN and 323 kN, respectively. It was unexpected that the columns strengthened under load (C) had higher average resistance than the columns welded without preload (B). It could be caused by the residual stress and distortion caused by welding. The study includes the results of finite element models of the problem created in ANSYS software. The results from the experiments and numerical simulations were compared.

1. Introduction

Strengthening of steel members using welded plates is a common praxis because it is a fast and cheap method. Unloading of the structure may often be hardly feasible or economically inconvenient and then strengthening under load is carried out. Although there are several rules of thumb, current normative documents do not refer to this problem and no reliable analytical solution has been developed up to date. Most authors until 1990 [1, 2] allow only elastic distribution of stress in the strengthened member. Unterweger [3] used finite element study to determine ultimate plastic resistance of the member strengthened under load. Vild, Bajer [4] modified the method to be more

² To whom any correspondence should be addressed.



conservative and in accordance with current Eurocodes. Unfortunately, no method copes with residual stress and deflection caused by welding, which seems to have a significant impact on the buckling strength. Unterweger suggests reduction of ultimate load capacity by around 10 %. On the other hand, Rao and Tall [5] observed increase of ultimate load capacity.

The paper presents experimental and numerical research on strengthening of columns under load using welded plates. The experiments were conducted at the laboratory of the Institute of Metal and Timber Structures at Brno University of Technology in December 2014.



Figure 1. Specimen in the load set-up.

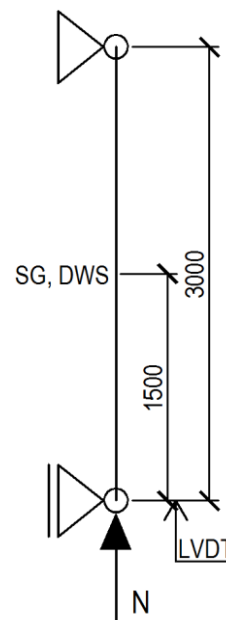


Figure 2. Loading scheme, LVDT, strain gauge (SG) and draw wire sensor (DWS) location.

2. Methods

Three sets of columns were selected for the research. The columns were subjected to compressive force (see figures 1 and 2). The cross-sections are presented in figure 3. All columns were welded with continuous weld with throat thickness 4 mm. Set (A) included columns with T shaped cross-section welded from the flange with dimensions 140×7.7 mm and the web with dimensions 200×6.3 mm. According to EN 1993-1-1 [6] classification of cross-sections, the columns of set (A) were class 4. Set (B) comprised the columns with monosymmetric I shaped cross-section. The flanges had dimensions 140×7.7 mm and 80×8.0 mm and the web 200×6.3 mm. This cross-section was class 2. Sets (A) and (B) were necessary for comparison of behaviour and resistance. Set (C) contained the columns with T shaped cross-section with the same dimensions as the columns in set (A). The columns from set (C) were first loaded to 70 kN and then strengthened under load with the second flange. The resulting cross-section was the same as of the columns from set (B).

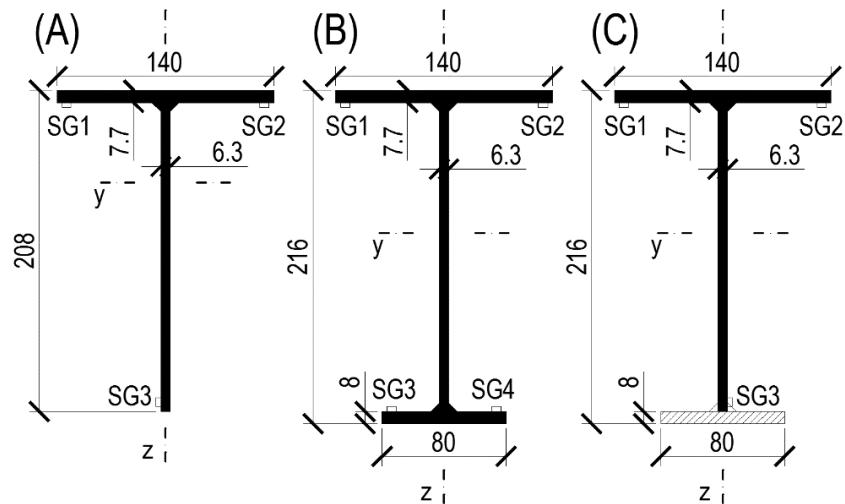


Figure 3. Column sets with dimensions and strain gauges (SG) position.

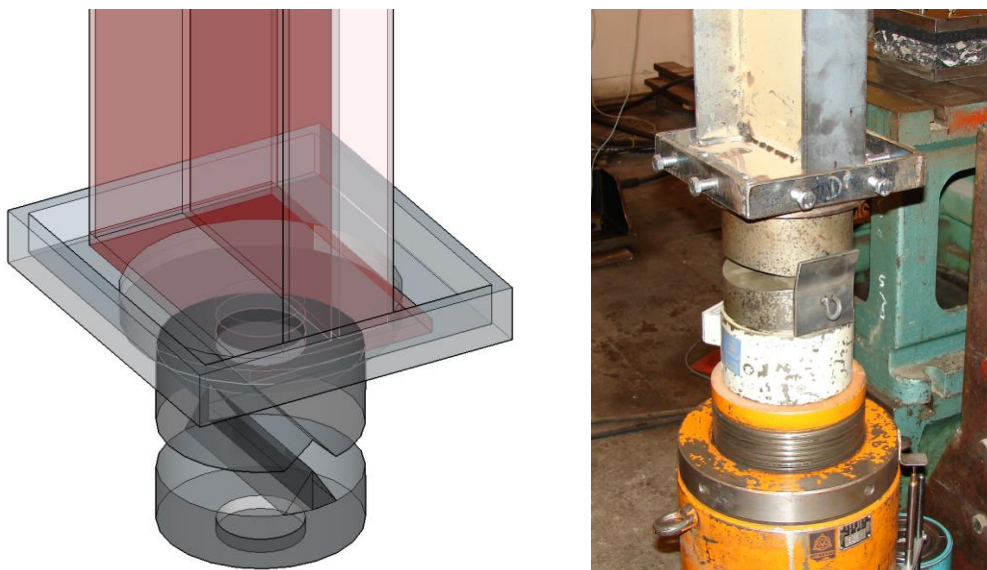


Figure 4. Scheme and photograph of the knife-edge boundary condition.

2.1. Analytical solution

The buckling resistance was determined by procedure from EN 1993 [6]. Length of the column plus knife-edge bearings thickness was used as buckling length in direction perpendicular to the weaker axis and half of this value in direction perpendicular to the stronger axis and in torsion. No additional bending moment was included. The buckling resistance of set (A) and set (B) is 159 kN and 269 kN, respectively.

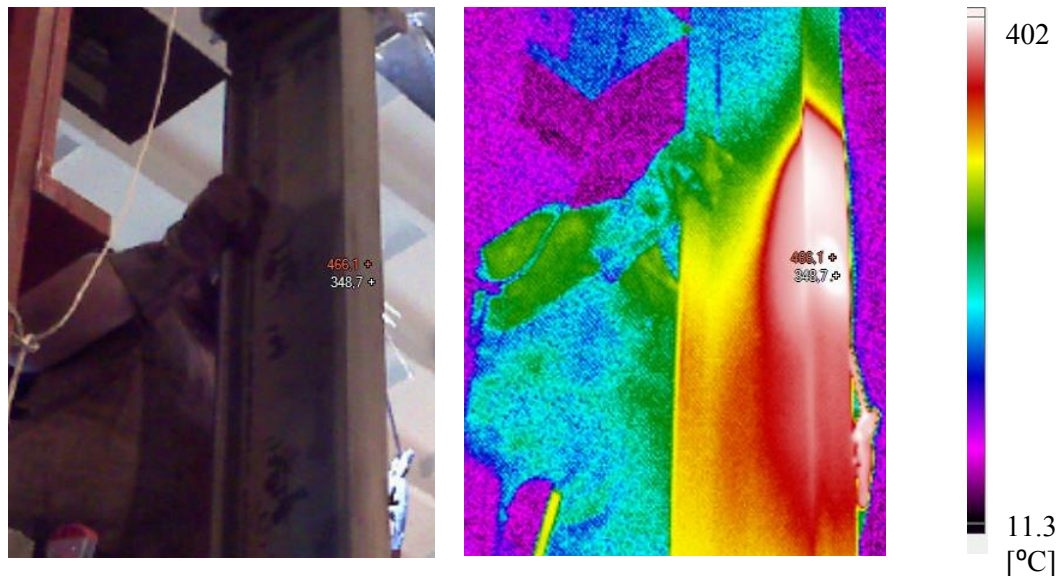


Figure 5. Welding process and thermal image.

2.2. Experimental research

Each set comprised three columns for experimental research. All columns were 3 m long and loaded by loading cylinder. The load was transmitted through knife-edge bearings, which ensured pinned boundary condition perpendicular to the weaker axis and fixed perpendicular to the stronger axis (see figure 4). Both sets (A) and (B) had been loaded monotonically until collapse occurred. The columns from set (C) were first inserted into the loading set-up and loaded to 70 kN. The force was held roughly constant (± 5 kN) and the second flange with dimensions 80×8 mm was being welded to the web under the load. The shielded metal arc welding method was used. The force was rising by around 1 kN per 12 s while the steel was being heated by the welding process and dropped at the same rate while the process was paused and the column cooled. The temperature of the column was monitored with thermal imager (see figure 5). After the welding process was finished and the specimen cooled, the column was unloaded to 10 kN and then loaded to failure.

Strain gauges 1-LY11/6/350 were used (see figure 3). The vertical displacement and force at the bottom and the horizontal deflection and strains in the middle of the height were measured in case of all specimens. Tension coupon tests were conducted to determine steel mechanical properties. Four coupons were machined from webs and four from flanges. Precise thickness of plates was measured with callipers on several spots and the average value was used for analytical and numerical analysis. South well plot [7] was used to determine the initial imperfections.

2.3. Numerical modelling

Numerical simulations were performed to complement the values which have not been measured in the experiment. ANSYS software [8] was used for finite element analysis. SHELL 181 element type was used for all plates. The true stress strain diagrams obtained from the coupon tests were used for two material models – one for flanges and another one for webs. First, the ideal geometry was created and then it was updated with imperfections using Block Lanczos modal analysis. The first mode was selected with maximum deflection 5 mm, which is equal to 1/600 of the column length and roughly coincides with the results of Southwell plot. Pinned boundary conditions and node coupling in the

longitudinal direction were used at the position of the knife-edge bearings. Then the elements were switched to SHELL 131 and two thermal analyses were conducted. The first was for the residual stress distribution of the base T shaped cross-section, the second was for deflections and residual stress caused by welding of the strengthening flange under load (see figure 6). Then the elements were changed again to structural and five consecutive static analyses were performed. First, the elements of the strengthening plate were deactivated and the residual stress for the base T shaped cross-section was implemented. Second, the column was loaded to 70 kN. Third, the elements of the strengthening plate were reactivated and residual stress and deflection caused by the welding process were implemented. Fourth, the column was unloaded to determine the change of initial imperfections of the column strengthened under load. Finally, the column was loaded with force until the solver stopped converging, meaning collapse was reached.

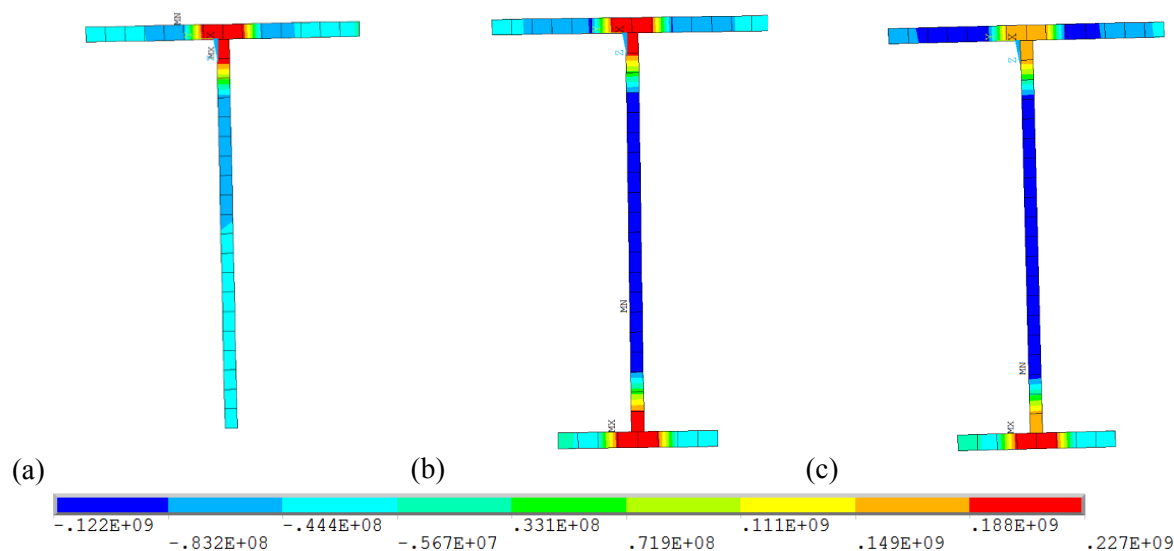


Figure 6. Residual stress from welding in longitudinal direction at the middle column height: set (a) – without load; set (b) – without load; set (c) – with preload 70 kN.

3. Results and discussion

3.1. Experimental research

The results of mechanical properties were averaged and summarized in table 1. The web steel seemed to be of slightly higher quality than the flange steel.

Table 1. Mechanical properties from coupon tests.

	E [GPa]	f_y [MPa]	f_u [MPa]
Web	211	334	480
Flange	203	310	457

Stress recalculated from strain gauges and deflections from draw wire sensors at the moment of collapse are plotted in figure 7, graphs of deflections dependent on axial force are shown in figure 9, note that deflections are in absolute values. All specimens failed by torsional-flexural buckling as expected (see figure 8) but the load, stress and deflection at collapse show great scatter.

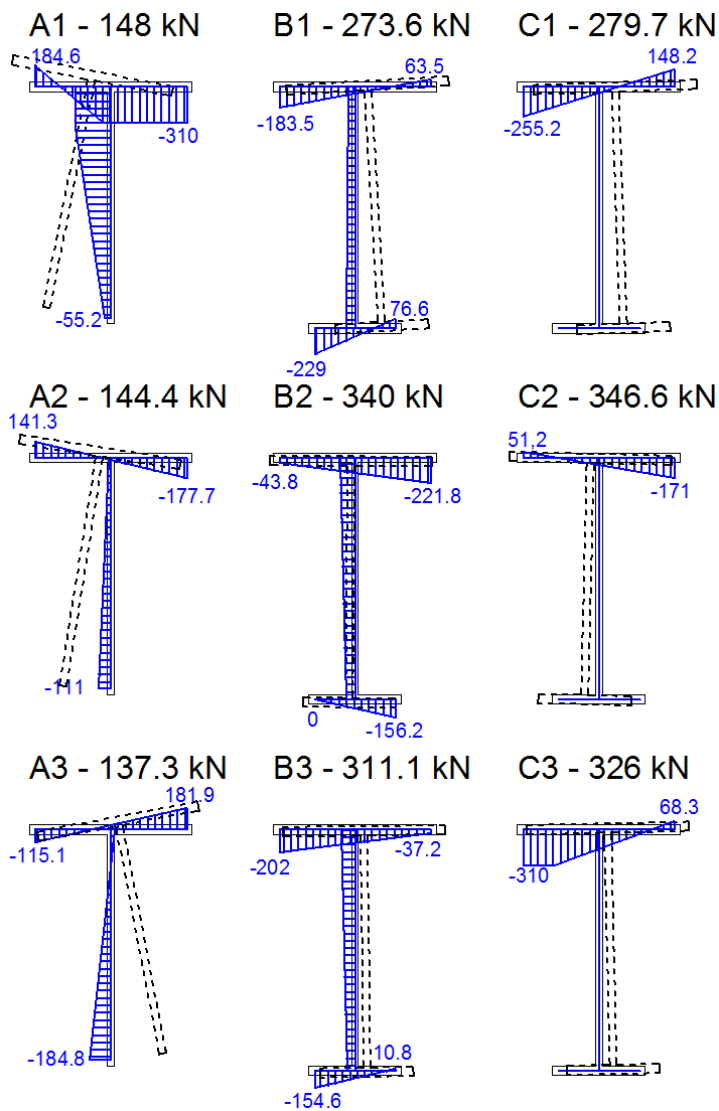


Figure 7. Stress recalculated from strain gauges and deflection at the moment of collapse.



Figure 8. Collapsed column.

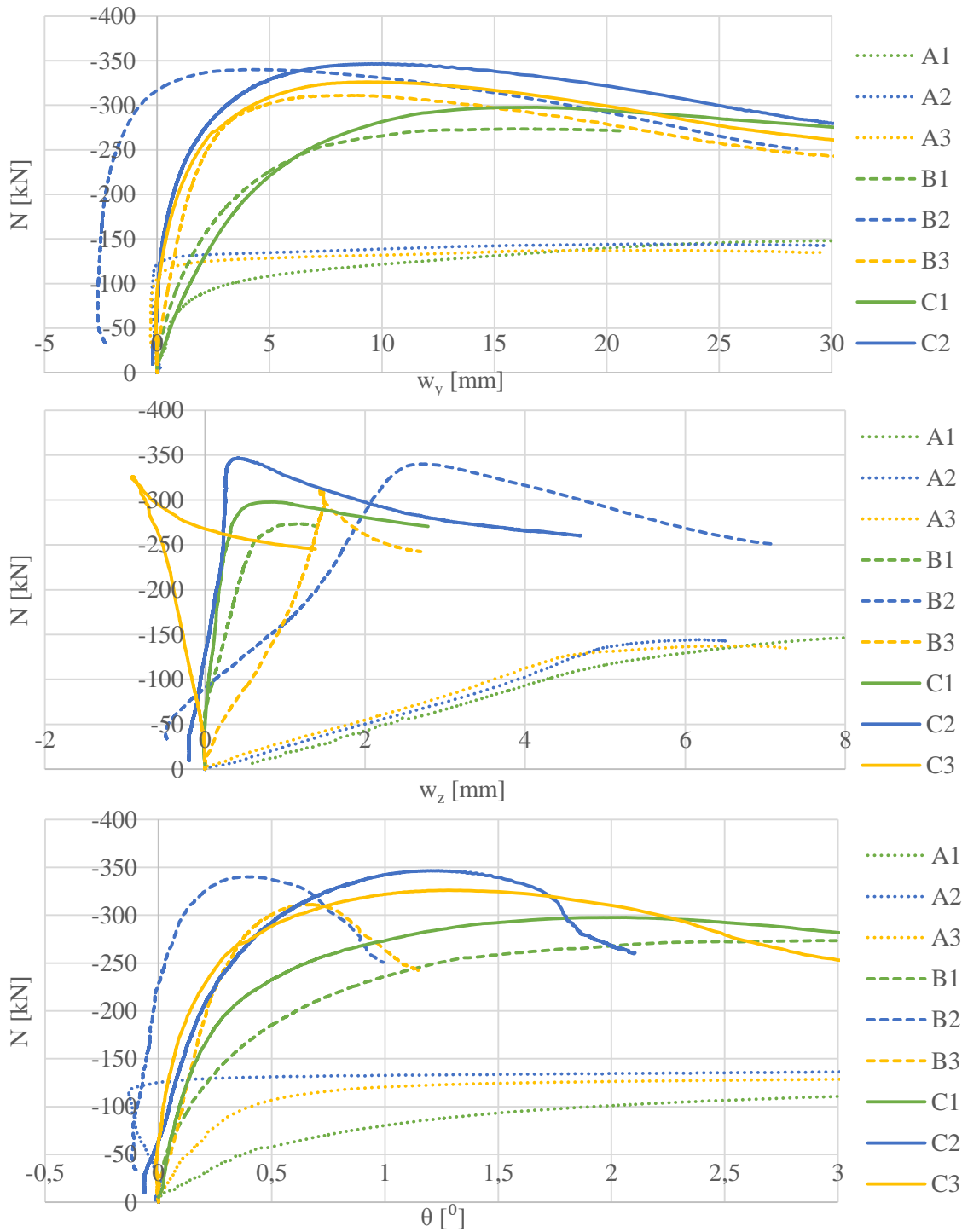


Figure 9. Graphs of deflections in the direction of stronger axis y and weaker axis z and rotation ϑ .

The average stress on the flange of the base T shaped cross-section (average of SG1 and SG2) at load 70 kN was only -5 MPa (compression). The stress after the welding process even switched into tension to average value 18 MPa (tension). The stress on the web of the base T shaped cross-section (SG3) was -93 MPa, which is still a low value compared to the yield stress. The welding process near SG3 unfortunately destroyed the strain gauge but the weld clearly caused shrinkage. The specimens from set (C) deflected at the middle height by welding by average value -10.63 mm in z direction. The average ultimate load capacity of set (B) was 308 kN and of set (C) 323 kN. In the case of these 6 specimens, the resistance of the column strengthened under load (C) even increased compared to the column with I shaped cross-section welded without preload (B). This could be explained by the effect of residual stress and deflection caused by welding, which slightly returned the column to the original shape and caused the tension in the most compressed base section flange. This behaviour and increase of ultimate load capacity was also observed, for example, by Rao and Tall [5].

3.2. Numerical modelling

The numerical results coincide closely with the experiment. Von Mises stress at the moment of collapse is shown in figure 10. Deflections are plotted in figure 11; note that deflections are in absolute values and deflections caused by welding are set to zero in the case of experimental results, while in the numerical simulation all the processes – welding of T shaped cross-section, loading to 70 kN, welding of the strengthening flange, unloading and loading to failure – are plotted.

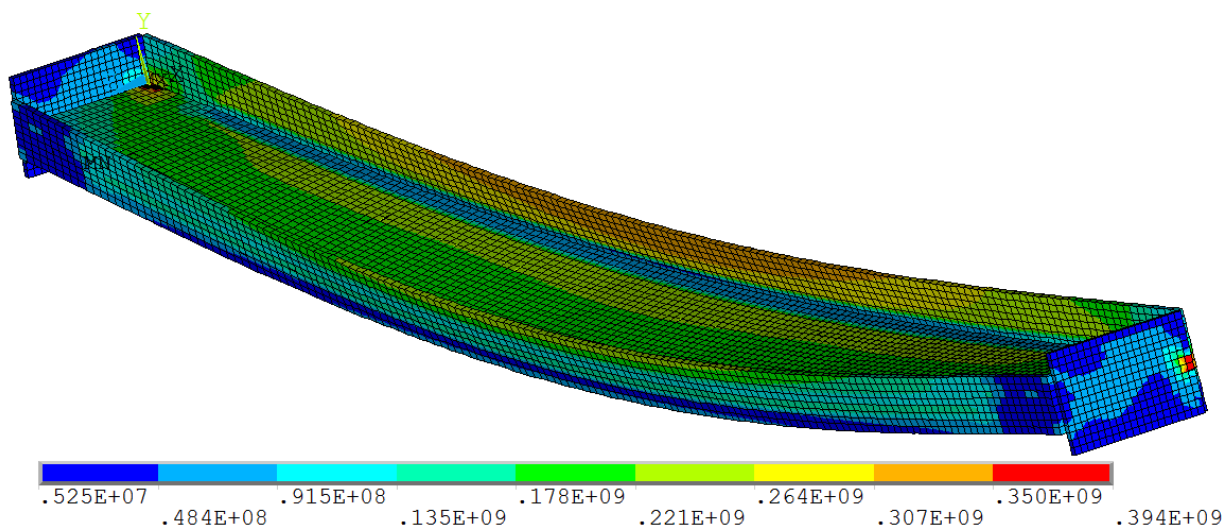


Figure 10. Von Mises stress distribution for the column from set (c) at failure (deflection scale 5).

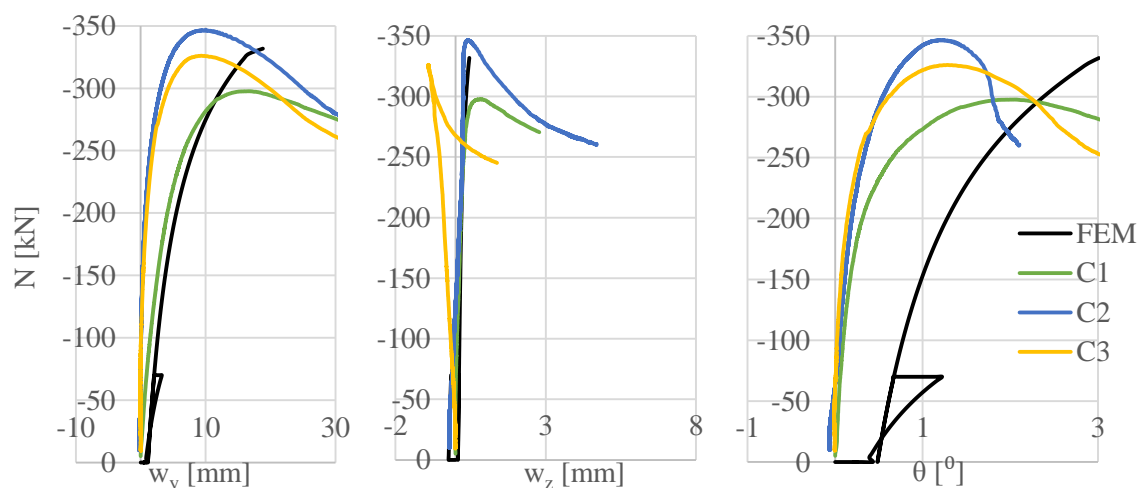


Figure 11. Comparison of experimental and numerical results of deflection.

Additional simulations were made to determine the effect of residual stress and preload on the ultimate load capacity of the column. The preload 70 kN decreased the ultimate load capacity by only 2.7 %, therefore, the increase in resistance observed from the experiment is not confirmed. The residual stress decreased the load capacity of the column with I shaped cross-section and the column with T shaped cross-section but the implementation of residual stress at the preload indeed showed increase of resistance by 6.3 %.

The sensitivity analysis was performed by Kala [9]. It showed that residual stress has the highest impact on columns with relative slenderness around 0.7. The relative slenderness of the specimens was higher (1.8 for T shaped and 1.5 for I shaped cross-section). At this relative slenderness, axis curvature has the highest impact but residual stress is more determinant than, for example, material yield strength.

4. Conclusion

The experiments proved that strengthening of the column with T shaped cross-section under preload up to 50 % of the base section buckling resistance is safe and feasible. However, the force rises rapidly if the welding process is fast. Thus, temperature changes must be carefully monitored and stress changes considered especially if the column is less stiff than the surrounding structural components.

The numerical simulation serves to determine the values that had not been measured or are unclear in the experiment. The validated numerical model will serve for the behaviour analysis of members strengthened under load in future research in this area, which is in progress and other experiments have already been planned.

The results of the T shaped cross-section columns require further research. The buckling resistance with the consideration of additional moment caused by local buckling according to the Eurocode [6] (88.5 kN) is extremely conservative, but the resistance without additional moment (159 kN) is too high compared to the experiment.

5. References

- [1] Spal L 1968 *Rekonstrukce Ocelových Konstrukcí* (Prague: Státní nakladatelství technické literatury) p 183
- [2] Rircker T D 1988 Field welding to existing steel structures *Engin. J.* 16
- [3] Unterweger H 1999 Ultimate load capacity of columns strengthened under load *Advances in Steel Struct.* 117–124
- [4] Vild M and Bajer M 2015 Flexural buckling of columns strengthened under load *Advanced Mat. Research* 4
- [5] Nagaraja Rao N R and Tall L 1963 Columns reinforced under load *Welding Research Council, Welding Research Supplement* 177–85
- [6] ČSN EN 1993-1-1 Eurokód 3: Navrhování ocelových konstrukcí – Část 1-1: Obecná pravidla a pravidla pro pozemní stavby 2011 (Prague: ČNI) p 94
- [7] Southwell R V 1932 On the Analysis of Experimental Observations in Problems of Elastic Stability *Proc. Roy. Soc. London Series A* pp 601–616
- [8] ANSYS® Academic Research, Release 15.0, Help System, ANSYS Parametric Design Language Guide, ANSYS, Inc.
- [9] Kala Z and Kala J 2011 Sensitivity Analysis of Stability Problems of Steel Structures using Shell Finite Elements and Nonlinear Computation Methods ICNAAM *AIP Conf. Proc.* vol 1389 pp 1865–68

Acknowledgement

The financial support of projects FAST-J-15-2859, TA03010680 and No. LO1408 “AdMaS UP - Advanced Materials, Structures and Technologies”, supported by Ministry of Education, Youth and Sports under the “National Sustainability Programme I” are gratefully acknowledged.