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Procedia Engineering 190 (2017) 118 – 125

Procedia Engineering

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Structural and Physical Aspects of Construction Engineering

Strengthening under Load: Numerical Study of Flexural Buckling of Columns

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Abstract

The paper refers to the strengthening of doubly symmetric columns under load by welded plates. A validated numerical study containing more than 500 models was performed to question the currently used design procedures. These procedures are not unified but vary greatly in different countries. The overly conservative design approach used in the Czech Republic contrasts with the approach completely neglecting the effect of preload commonly used in the USA. The effect of various parameters on the flexural buckling resistance of columns strengthened under load was investigated. The selected parameters were the thickness of the strengthening flange, the column length, the initial bow imperfection, the preload magnitude and the direction of the axis which is pinned while the other axis is fixed. Several conclusions were reached from provided results and a simple analytical method is proposed. The load under which the column is strengthened weakens the column but only slightly.

Peer-review under responsibility of the organizing committee of SPACE 2016

Keywords: Column; experiment; finite element analysis; parametric study; steel; strengthening under load

1. Introduction

This paper investigates strengthening of steel members under load using welded plates. It focuses on flexural buckling of doubly symmetrical axially loaded columns. The paper contains a description and results of experimental research performed in years 2015 and 2016 which served to study the feasibility of column strengthening under high magnitudes of preload (the load under which the column is strengthened), the temperature changes raised by welding

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Peer-review under responsibility of the organizing committee of SPACE 2016
doi:10.1016/j.proeng.2017.05.316

process and the size of affected area, and to validate the numerical models used for parametric study. The results are compared with two vastly different analytical approaches.

The first, used in the USA [1], presumes that the strength of columns strengthened under preload and under no load is identical. This claim is supported by various researchers, e.g. O'Sullivan [2], Nagaraja Rao and Tall [3], Tide [4], Wu and Grondin [5]. The second approach does not allow the steel of the base section to yield in the case of members susceptible to buckling. It was introduced by Spal [6] and later adopted by Czech technical recommendations [7] and other authors, e.g. Vašek [8]. This safe approach is supported by e.g. Brown [9] and Ricker [10]. The design of a member under high preload magnitude according to the first or second approach leads to completely different cross-section and use of material. This big discrepancy may be caused by only several experimental studies in this area.

To author's knowledge, experiments of strengthening steel compressed members under load are very scarce and were conducted by O'Sullivan [2] (2 specimens strengthened under compressive load, bolted plates, very low effect of buckling), Kolesnikov [11] (3 specimens, high preload magnitudes, no comparison with member strengthened under no load), Nagaraja Rao and Tall [3] (1 specimen, complemented with stub column tests), Marzouk and Mohan [12] (7 specimens, high preload magnitudes, no comparison with member strengthened under no load) and authors [13, 14] (6 specimens, torsional-flexural buckling and local buckling).

The authors believe that the load resistance of steel members strengthened under load is decreased by the effect of preload but only slightly. There are two factors that should be accounted for in the structural design:

- Increased initial deflection caused by lower stiffness of the base section compared to the strengthened section as suggested by Unterweger [15]; distortion caused by asymmetric welds [16] added to this increased bow imperfection.
- Residual stress caused by welding (hardly predictable) and preload.

The exact solution is difficult and contains some hardly predictable variables for practical design. Therefore, a simple solution with a coefficient *k* is introduced.

Nomenclature

A_0	area of a base cross-section
A_z	gross area of a strengthened cross-section
L	column length
N_1	preload magnitude
$N_{b,0,Rk}$	load resistance of a base member
$N_{b,z,Rk}$	load resistance of a strengthened member
$N_{s,R}$	load resistance of a member strengthened under preload
f_y	yield strength of used material
k	coefficient adjusting the effect of preload magnitude
χ_0	buckling reduction factor of the base section
χ_z	buckling reduction factor of the strengthened section

2. Methods

2.1. Experimental research

Experimental research took place at the laboratory of the Institute of Metal and Timber Structures at Brno University of Technology in years 2015 and 2016. Hot rolled steel section HEA 100 was selected as the base section and strengthening plates with cross-section dimensions 120×10 mm were used. The cross-sections along with strain gauges and draw-wire sensor positions are shown in Fig. 1. All columns were 3 m long and all steel was grade S235 (yield strength from coupon tests: 309 ± 4 MPa – base section, 294 ± 6 MPa – strengthening plates; modulus of elasticity was not measured and was estimated 210 GPa). The boundary conditions were determined by knife-edge bearings along axis *z*; the column was therefore pinned perpendicular to axis *z* and fixed perpendicular to axis *y*. The strengthening plates were welded using intermittent welds with throat thickness 4 mm. The experimental procedure, boundary conditions and measuring devices are described in greater detail in previous article by authors [17]. Two strengthening patterns were selected: (O) with strengthening plates perpendicular to the flanges of the base section and (H) with strengthening plates parallel to the flanges. Each set with the distinguished pattern contained six specimens. Two columns from each set were welded on a bench without preload and loaded to failure, other four columns were strengthened under load using following procedure:

1. Strengthening plates were welded to the base section with one short weld at mid-height and then strain gauges were glued.
2. A column was inserted into the loading frame, all measuring devices were activated and the column was loaded to desired preload (see Table 2).
3. The strengthening plates were fastened into position using C-clamps and then welded to the base section using intermittent welds. The welding procedure took around an hour and the preload was manually adjusted to mitigate the thermal expansion and oil leakage from the loading cylinder.
4. The column cooled for about an hour and then was loaded to failure.

The preload ratios (ratio of preload and load resistance of the base section) were selected from 0.46 to 0.93.

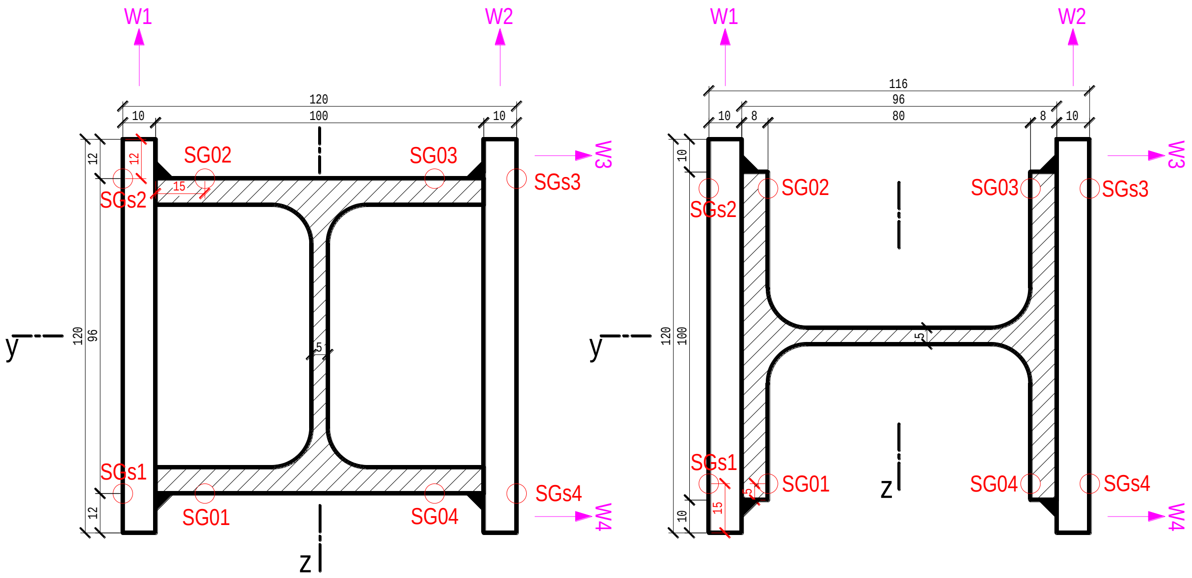


Fig. 1. Cross-sections of specimens (base section is hatched) with positions of strain gauges (SG) and draw-wire sensors (W) on the cross-section at mid-height; strengthening pattern O on the left, pattern H on the right.

2.2. Numerical research

Numerical analysis was conducted using ANSYS® Academic Research, Release 16.2 software. Description of models and their validation are described in detail in [17]. For the parametric study, four node SHELL 181 element type and the bilinear isotropic material model with Young's modulus of elasticity E = 210 GPa, yield strength f_y = 235 MPa and nominal yielding plateau slope 21 MPa were used in all cases. Note that the strengthening flanges had the same width as the base section column flange in the parametric study (see Fig. 2). Variable parameters were summarised in Table 1. Not all parameters were combined with each other but regardless the study contains 574 numerical models. The range of relative slenderness $\bar{\lambda}$ was 0.523–2.061 and 0.439–1.992 for base section and strengthened section, respectively.

Table 1. Variable parameters in numerical parametric study.

Column length	2, 3, 4, 5 m
Strengthening pattern	O, H
Pinned axis	strong axis, weak axis
Preload magnitude (pattern H, pinned perpendicular to the strong axis)	30 kN steps for 5 m length, 50 kN steps otherwise
Preload ratios (pattern H, pinned perpendicular to the weak axis)	0.2, 0.4, 0.6, 0.8
Preload ratios (pattern O)	0.25, 0.5, 0.75
Equivalent initial bow imperfection	*L*/200, *L*/300, *L*/600
Thickness of strengthening plates	4, 8, 10, 12 mm

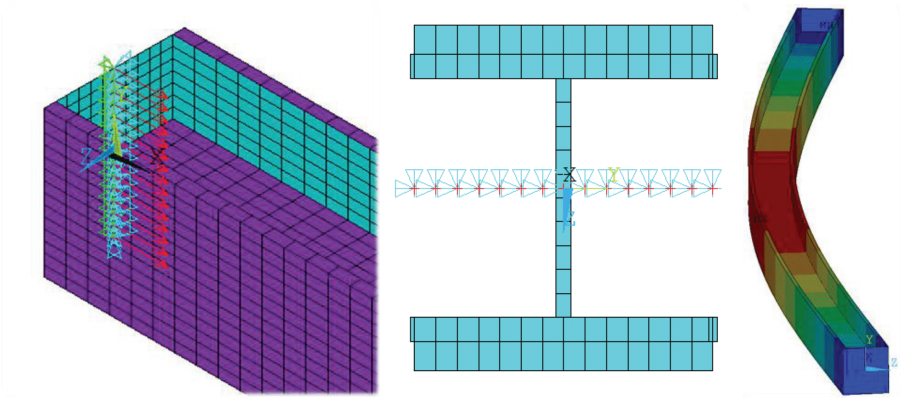


Fig. 2. Mapped mesh, boundary conditions and the first eigenvalue shape of the column strengthened with pattern H used in parametric study.

2.3. Analytical solution

The simple analytical solution is based on the formula used in Czech technical recommendations [7] extended by a coefficient *k*, which diminishes the effect of preload on the load resistance of the member strengthened under preload:

$$\frac{k \cdot N_1}{N_{b,0,Rk}} + \frac{N_{s,R} - k \cdot N_1}{N_{b,z,Rk}} = \frac{k \cdot N_1}{\chi_0 \cdot A_0 \cdot f_y} + \frac{N_{s,R} - k \cdot N_1}{\chi_z \cdot A_z \cdot f_y} \leq 1 \tag{1}$$

From Equation (1) a coefficient *k* can be determined:

$$k = \frac{\dfrac{N_{b,0,Rk} \cdot \chi_z \cdot A_z}{N_1} - \dfrac{N_{s,R} \cdot \chi_0 \cdot A_0}{N_1}}{\chi_z \cdot A_z - \chi_0 \cdot A_0} \tag{2}$$

Coefficient *k* equal to 1 leads to elastic design; *k* equal to 0 leads to complete neglect of the effect of preload. Equation (2) serves to obtain *k* from numerical analyses and then, after statistical evaluation, a characteristic coefficient *k* can be used to evaluate the resistance of the member strengthened under load $N_{s,R}$ using Equation (3).

$$N_{s,R} = N_{b,z,Rk} - k \cdot N_1 \cdot \left(\frac{N_{b,z,Rk}}{N_{b,0,Rk}} - 1 \right) \tag{3}$$

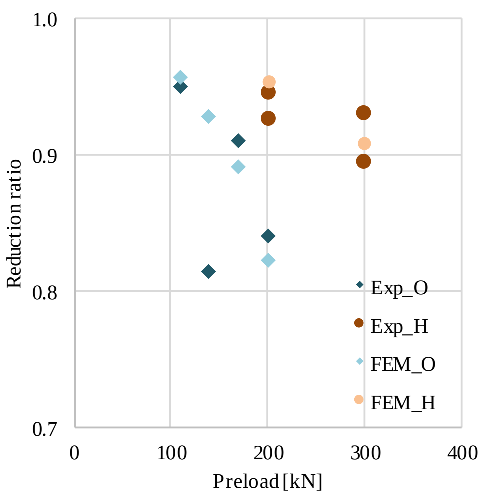
3. Results and discussions

3.1. Experimental research

Using the thermochalk, the area of the base cross-section affected by a temperature higher than 320°C near one weld was only 1 cm^2 (5 % of the base cross-section). Use of symmetrical intermittent welds and thin wire electrode contributed to this low impact of welding on column deflection and elongation during welding and hence the material degradation could be neglected. On the other hand, the weld cooled very fast which can lead to occurrence of brittle martensite [18]. The welding process is captured in Fig. 3. Welds did not fail in any case even at large deflections after the collapse.

Table 2. Overview of specimens used in experimental research, their load resistances and comparison with finite element models and suggested analytical method.

Column	Preload [kN]	Preload ratio	Load resistance [kN]	Reduction ratio	FEM Load resistance [kN]	$N_{s,R}$ (k = 0.5) [kN]
O1	0	0	1084		960	877
O2	0	0	1076		960	877
O3	200	0.93	907	0.84	790	570
O4	170	0.79	983	0.91	892	616
O5	140	0.65	880	0.81	855	662
O6	110	0.51	1027	0.95	919	708
H1	0	0	994		1046	1020
H2	0	0	1083		1046	1020
H3	200	0.46	982	0.95	999	884
H4	300	0.69	930	0.90	951	816
H5	200	0.46	962	0.93	999	984
H6	300	0.69	967	0.93	951	816



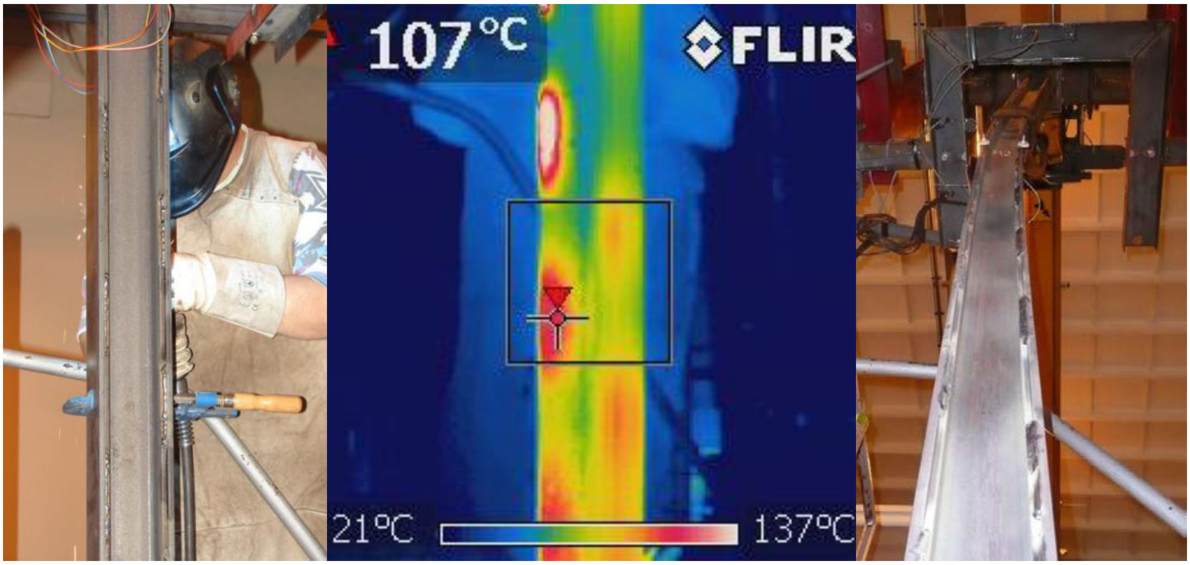


Fig. 3. Gas metal arc welding of intermittent welds captured by a camera and a thermal imager; buckled column H2.

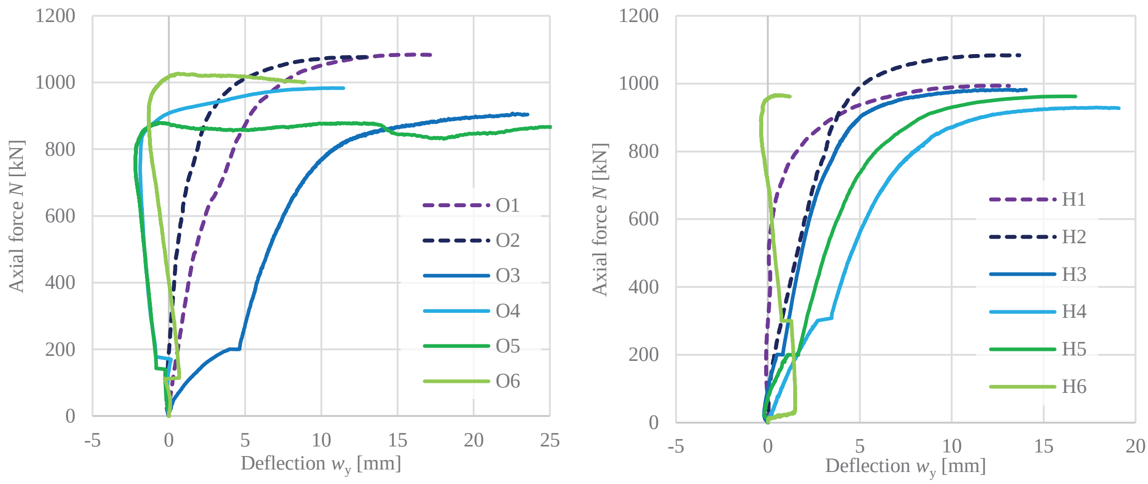


Fig. 4. Load–deflection curves of columns in experimental research; columns strengthened without preload are marked with dashed lines.

The analytically determined buckling resistances according to EN 1993-1-1 [19] using the yield strength determined from tensile coupon tests are for the strengthening pattern O $N_{b,0,Rk}$ = 215 kN and $N_{b,z,Rk}$ = 877 kN and for the strengthening pattern H $N_{b,0,Rk}$ = 432 kN and $N_{b,z,Rk}$ = 1020 kN. Experimental load resistance which is lower than the analytical buckling resistance is highlighted in red colour in Table 2. Note that the resistance of the base section was determined using standard procedure by EN 3 [19]. The experimental resistance would probably be slightly higher and thus the preload ratios lower. The reduction ratio is the ratio of the load resistance of column strengthened under load to the load resistance of column welded without preload. The load–deflection curves are in Fig. 4. The load resistance of columns strengthened under preload was in all cases smaller than the load resistance of columns welded without preload. All columns failed via flexural buckling as expected with one exception of column H6 which buckled around axis *y* despite the orientation of knife-edge bearings. This case shows that knife-edge bearings cannot ensure fixed boundary condition. To equalise critical loads perpendicular to both axes, the buckling length for the direction around the "fixed" axis should be equal to 1924 mm (3000/1.56). In the case of the column O3 (preload ratio 0.93), the base section deflected by nearly 5 mm (*L*/600), which is a significant deflection and strengthening under such high preload ratios cannot be recommended.

3.2. Numerical research and analytical solution

Using results of numerical models and Equation (2), coefficient *k* can be determined for each column strengthened under load. The distribution of coefficient *k* is shown in Fig. 5 and Fig. 6.

Coefficient *k*	
Average	0.230
Median	0.216
Minimum	-0.075
Maximum	0.716
95% quantile	0.488
Number of samples	382

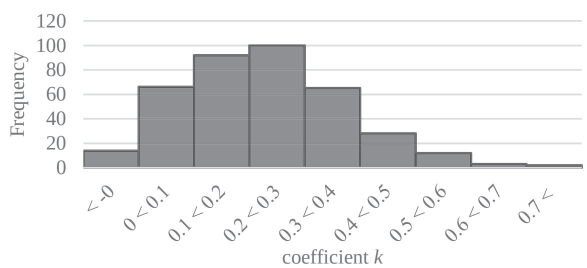


Fig. 5. Distribution of coefficient *k* depicted in a histogram.

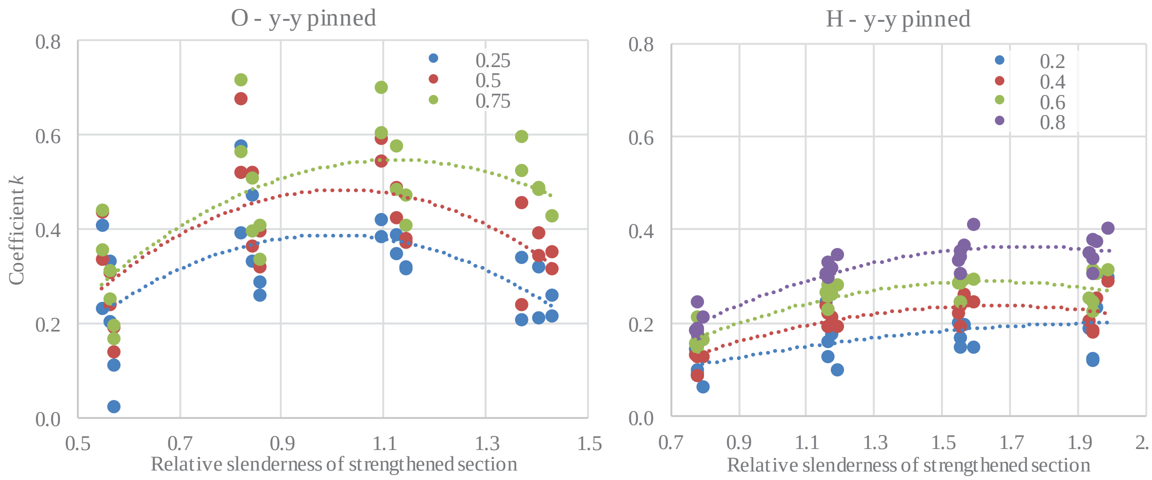


Fig. 6. Coefficient *k* in dependence on relative slenderness of the strengthened section; preload ratios are marked with distinctive colour.

The buckling curves in EN 1993-1-1 are designed so that the biggest impact of initial imperfections is at relative column slenderness $\bar{\lambda} = 1$. Kala and Kala [20] used sensitivity study on various initial imperfections and concluded that for hot-rolled I shaped column IPE 220 residual stress is the most important factor at $\bar{\lambda} = 0.68$ and initial crookedness at $\bar{\lambda} = 0.97$. It seems that the coefficient *k* is the highest at higher relative slenderness, from 1 to 2 (see examples in Fig. 6). That means the preload affects the reduction ratio the most at this relative slenderness from 1 to 2. Authors presume that the stress locked in by the strengthening under load has a greater effect at low relative slenderness and with increasing slenderness the effect of increased initial deflection is becoming more significant.

The correlation of coefficient *k* on base section or strengthened section slenderness or thickness of strengthening plates is not completely clear yet. Therefore, authors suggest a use of $k = 0.5$, which is slightly safer value than 95% quantile (see Fig. 5). Comparison of numerical analyses with two analytical methods – (k) suggested method with coefficient $k = 0.5$; (TP) method according to [7] – is shown on the example of base section HEA 100 strengthened via plates thickness 10 mm with pattern H, pinned around axis *z* and initial imperfection *L*/300 in Fig. 7.

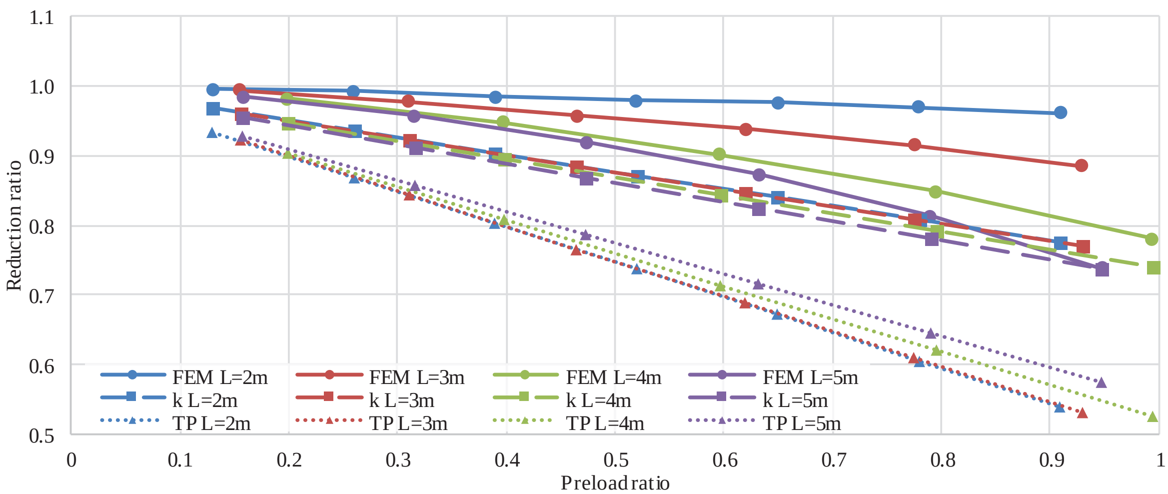


Fig. 7. Comparison of numerical models with analytical methods of strengthening under load.

4. Conclusions

Strengthening under load using welded plates is a feasible method. Use of thin electrode wire is recommended for strengthening under load to keep the heat affected zone small and to limit the elongation of the steel member during a welding process and shrinkage after cooling.

The simple analytical solution with a coefficient k was introduced. Based on the comprehensive numerical parametric study validated by experimental research, the value of coefficient k is suggested equal to 0.5. This method yields safe results and allows material savings compared to the commonly used method in the Czech Republic. Completely neglecting the effect of preload as suggested by some researchers seems hazardous.

Strengthening under preload ratios higher than 0.8 is in some cases feasible but not recommended, because the deflection caused by preload and welding can lead to significant deflections which could affect serviceability. Nevertheless, the reduction of load resistance in the experiment was only 19 % for preload ratio 0.93.

Acknowledgements

The financial support of projects No FAST-J-16-3560, FAST-S-16-2994 and GA14-25320S are gratefully acknowledged.

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