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## Strengthening under Load: The Effect of Preload Magnitudes

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### Abstract

Strengthening existing structures under load by welding plates is often conducted but little research into this subject was presented. Some researchers claim that the column strengthened under load has the same ultimate capacity as the column welded without preloading. Others disagree and recommend safe design not allowing the steel to yield. The paper presents the parametric study of wide flange columns HEA 100 strengthened under load via two plates parallel to flanges conducted on numerical models validated by experiment. The varying parameters are thickness of strengthening flange, column length, initial bow imperfection, preload magnitude and direction of the axis which is pinned while the other axis is fixed. The experimental research consisted of two columns welded without preload and two columns strengthened under preload ratios (preload magnitude divided by base column ultimate strength) equal to 0.5 (200 kN) and 0.75 (300 kN). All columns were 3 m long and the boundary conditions were determined by knife-edge bearings which ensured pinned supports in the direction perpendicular to the strong axis and fixed perpendicular to the weak axis. All strengthening plates were welded to columns with intermittent welds. All columns failed via flexural buckling. The numerical models used for the parametric study were created in ANSYS software. Design values and procedures recommended by EN 1993-1-5, Annex C were used. The most commonly used steel grade S235 was selected for all plates. Shell 181 element type was used for mapped meshing of steel plates. Element birth and death feature was convenient to simulate strengthening under load.

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Equivalent initial bow imperfection of the first Eigen buckling shape was included, the model was loaded by force and geometrical and material nonlinear analyses were performed. From provided results some conclusions can be reached. The load under which the column is strengthened slightly weakens the column but not by far to the extent of design recommendations used in the Czech Republic. The reduction ratio (ultimate load capacity of column strengthened under load divided by ultimate load capacity of column welded without preloading) decreases with increasing preload magnitude and column slenderness. Surprisingly, the initial geometrical imperfection, while affecting ultimate capacity greatly, has almost no effect on the reduction ratio.

## 1. Introduction

The paper refers to steel members loaded by axial compressive force strengthened under load by welded plates parallel to flanges. Strengthening existing structures under load by welding plates is often conducted but little research into this subject was presented. Some researchers, e.g. Tall [1] claim that the column strengthened under load has the same ultimate capacity as the column welded without preloading. Others, e.g. Spal [2], Ricker [3], disagree and recommend safe design not allowing the steel to yield. This safe approach was adopted by technical recommendations TP 42 [4] in the Czech Republic.

Well documented experiments of strengthening under load are scarce. O'Sullivan [5] designed strengthening of bolted and riveted steel structure of Bristol hangar. He presumed no resistance decrease due to the procedure of strengthening under load on the basis of 12 experiments. Rao and Tall [6] performed experiments on wide flange compressed columns (8WF31). The column strengthened under load had even higher ultimate load resistance than the reference column by 5 % but it might have been caused by lower initial imperfections. Tall conducted comprehensive research on residual stress and its effect on compressed column ultimate load resistance. Marzouk and Mohan [7] executed 7 experiments on compressed columns (W200×27, W150×22) using two methods of strengthening. All strengthened columns exhibited greater ultimate load capacity than design buckling resistance calculated according to EN 1993-1-1: Clause 6.3 and it seems that weld beads at flange tips provide more favourable distribution of residual stresses as stated by Tall [1]. Liu and Gannon [8] tested 9 strengthened specimens by four-point bending and used validated numerical models for parametric study [9]. Authors conducted experiments of strengthening of thin-walled welded T-shaped columns strengthened via 2nd flange to monosymmetrical I-shaped columns [10]. The purpose was to investigate the influence of local buckling and torsional-flexural buckling on the ultimate load resistance of the column strengthened under load. The behaviours and resistances of strengthened columns and reference columns were found to be similar. Therefore, from the experimental research, although not very numerous, it seems that preload magnitude does not decrease the ultimate resistance of the column noticeably and the safe, elastic design approach is not necessary.

In this paper, the main results of an extensive parametric study conducted on numerical models created in ANSYS software and validated by experiments are presented. The study is focused on flexural buckling of centrally compressed columns. The purpose is to contribute to the body of knowledge about strengthening allowing safer and more cost-efficient design of strengthening under load with a deep understanding of the problem.

## 2. Methods

### 2.1. Description of the experiment

The experimental research was performed in the Test Laboratory of the Institute of Metal and Timber Structures of the Faculty of Civil Engineering, Brno University of Technology. All steel was grade S235 (yield strength: 309 MPa – base section, 294 MPa – strengthening plates; modulus of elasticity 210 GPa). Four columns, labelled H1, H2 (reference columns welded without preloading), H3 and H4 (columns strengthened under load), were tested. Specimens strengthened under load were tested using following procedure. Two strengthening plates (dimensions 120×10×2990 mm) were welded by 120 mm long welds at the mid-height to the base section – column HEA 100. The column was 3 m long and the strengthening plates were 10 mm shorter. Strain gauges were glued to the specimen at mid-height. The specimen was inserted in the testing set-up, consisting of the rigid frame, knife-edge bearings, loading hydraulic cylinder, load cell, LVDT at the bottom and four draw wire sensors at mid-height (see Fig. 1).

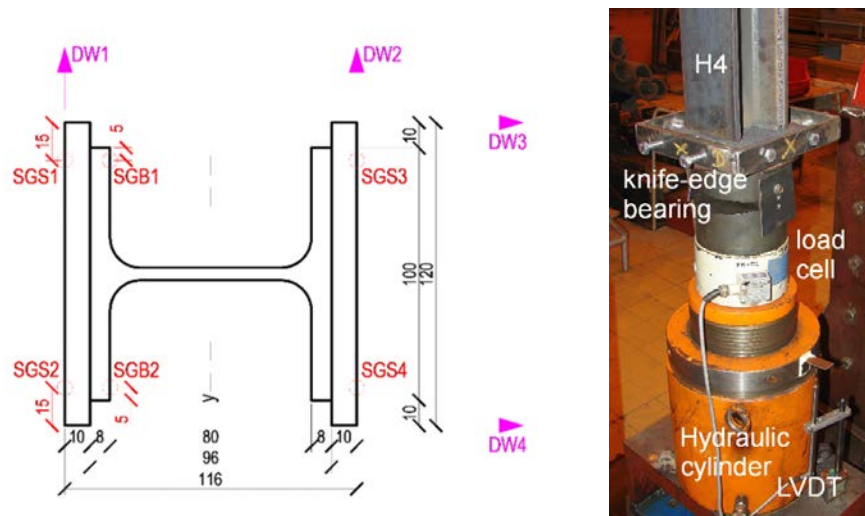


Fig. 1: (left) Column cross-section dimensions, (right) strain gauges (SGS, SGB) and draw wire sensors (DW) positions; specimen H4 in test set-up.

The edge bearings on the top and the bottom ensured pinned boundary conditions perpendicular to the strong axis and fixed perpendicular to the weak axis. All measuring devices were activated and the column was loaded to 200 kN and 300 kN in cases of specimens H3 and H4, respectively. Then, the force was held roughly constant while the strengthening plates were being welded to the base section column HEA 100 using intermittent welds. Gas metal arc welding procedure was used with wire thickness 1.2 mm. Only very small adjacent area of the steel was affected by welding. The column did not change length considerably and no significant distortions occurred. Thus, gas metal arc welding seems to be more convenient procedure than shielded metal arc welding with electrode thickness 2.3 mm, which was used by previous experimental research by authors [10] in which case the distortions and the temperature changes were much more serious. After the column cooled, the strengthened column was loaded to failure.

## 2.2. Description of the numerical models

Numerical modelling was performed using ANSYS® Academic Research, Release 16.2 software. Four node Shell 181 elements were used for all steel plates. Supports in all directions were added at the position of the upper knife-edge bearing and supports in horizontal directions and node coupling and force in longitudinal direction were added at the position of the lower knife-edge bearing. Eigenvalue analysis was performed and the geometry was updated with imperfections according to the first buckling shape. Then, the elements of the strengthening plates were deactivated (their modulus of elasticity was drastically reduced) and the base section was loaded to the desired preload magnitude. Next, the elements of the strengthening plates were reactivated and the force acting on the strengthened column had been increased until the solver stopped converging, i.e. the collapse occurred.

### 2.2.1. Parametric study

The procedures and design values recommended in EN 1993-1-5 Annex C were used. 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 was used in all cases. Variable parameters were summarized in Table 1. Not all parameters were combined with each other but regardless the study contains 334 numerical models.

Table 1. Variable parameters in numerical study.

column length	2, 3, 4, 5 m
pinned axis	strong axis, weak axis
preload magnitude (pinned perpendicular to the strong axis)	30 kN steps for 5 m length, 50 kN steps otherwise
preload ratios (pinned perpendicular to the weak axis)	0.2, 0.4, 0.6, 0.8
equivalent initial bow imperfection	$L/200, L/300, L/600$
thickness of strengthening plates	4, 8, 10, 12 mm

2.2.2. Validation of numerical model

The residual stress was neglected to keep the model as simple as possible. Due to symmetry of welds and use of intermittent welds, the neglect is justified. Therefore, the model was the same as in the parametric study. The size of the column and strengthening plates, boundary conditions, material properties and preload magnitudes corresponded to the experiments (see Chapter 2.1) and equivalent initial bow imperfection corresponded to  $L/450$ .

3. Results and Discussions

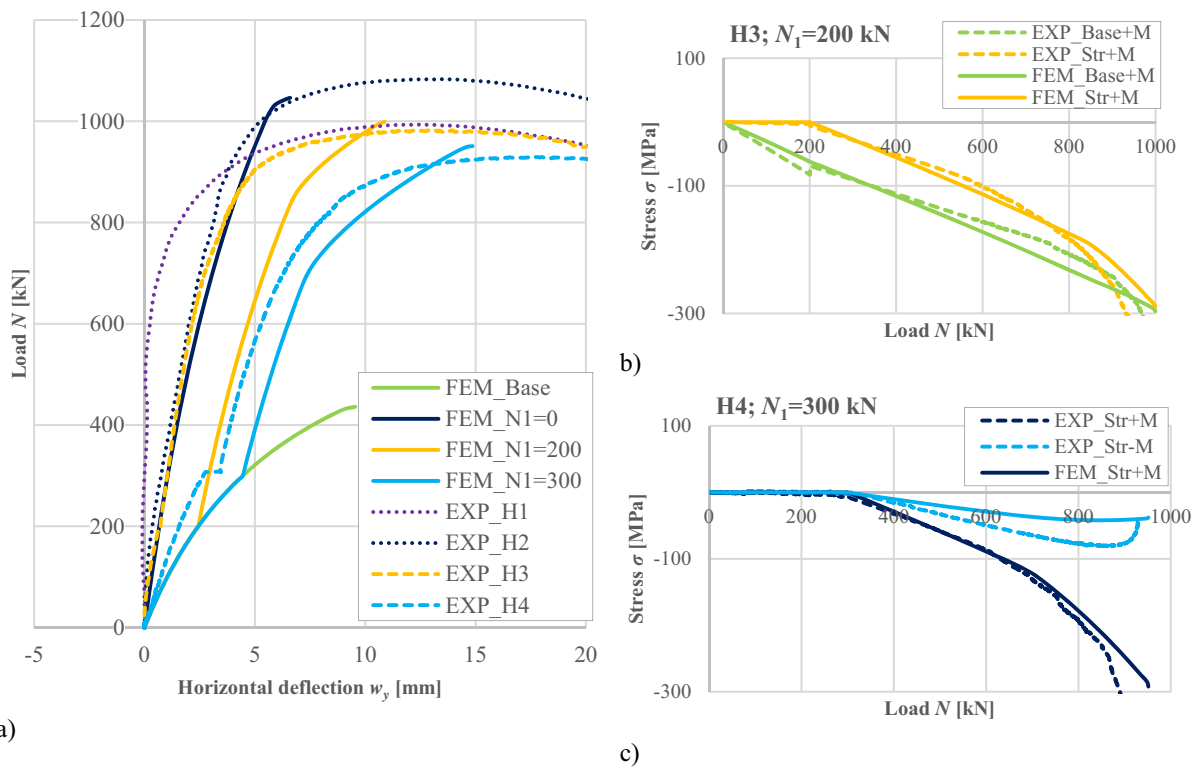


Fig. 2 a) Validation of numerical model – LD diagram and comparison of longitudinal stress  $\sigma$  on b) - flange of base section (Base), and c) at strengthening plate (Str).

The results of numerical and experimental research closely coincided, as can be seen in Fig.2. The load-displacement graph and strains in longitudinal direction captured by strain gauges were also found to be similar to numerical models. By contrast, the results of a design proposal from TP 42 [4] are extremely conservative and the reduction ratio decreases linearly with increasing preload magnitude, while the results of the numerical study show that the decreasing curve has approximately parabolic shape (see Fig. , a, b).

Table 2. Validation of numerical model – comparison of experimental, numerical (FEA) and analytical (according to TP 42) results.

Preload magnitude	Preload ratio	Experiment			FEA		TP 42		
		$N_{b,R}$ [kN]	Reduction ratio	$N_{b,R}$ [kN]	Reduction ratio	$N_{b,R}$ [kN]	Reduction ratio		
$N_j = 0$ kN	0.00	H1	994	average 1039	1.000	1046	1.000	850	1.000
		H2	1083						
$N_j = 200$ kN	0.50	H3	982		0.946	999	0.945	623	0.734
$N_j = 300$ kN	0.75	H4	930		0.895	951	0.904	510	0.600

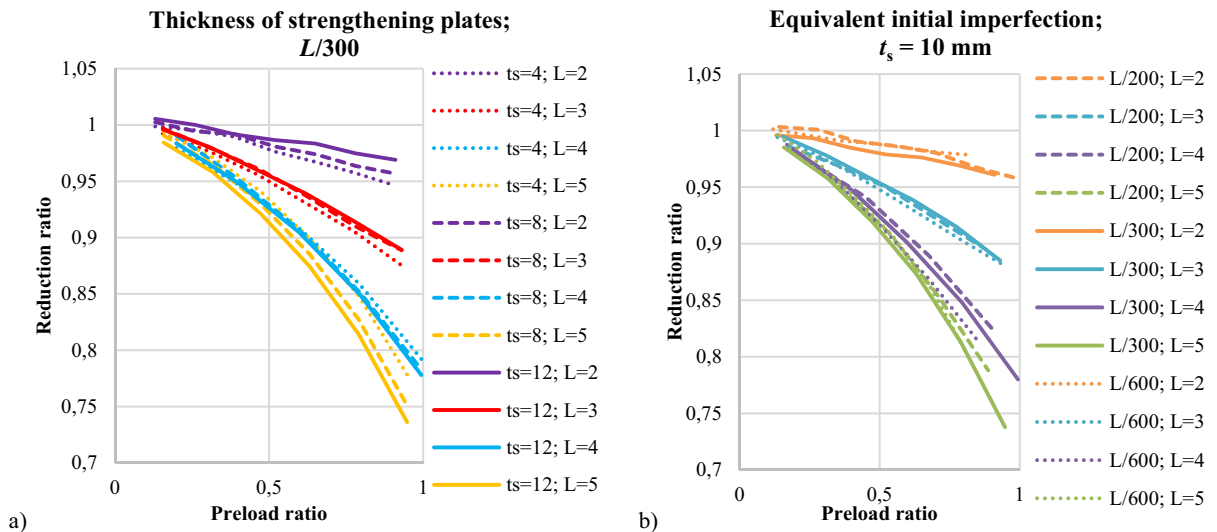


Fig. 3: Parametric study: thickness of strengthening plates  $t_s$  [mm] and equivalent initial imperfection, a) for L/300, b)  $t_s = 10$  mm.

It seems that the buckling resistance of strengthened column declines more rapidly with increasing preload and increasing column slenderness. The slenderness has a greater effect in the case of columns pinned perpendicular to the strong axis. On the other hand, the initial imperfection and the thickness of strengthening plates affect the reduction ratio only very little and these minor differences can be attributed to numerical errors (see Fig. ). The effect of preload magnitudes is not severe; the reduction ratio did not fall below 90 % for preload ratio 0.5 in any case.

#### 4. Conclusions

The effect of preload magnitudes on flexural buckling resistance of column strengthened under compressive load was investigated using numerical parametric study created in ANSYS software validated by experiments. Overall, the preload magnitudes have some effect on the buckling resistance of the strengthened column but the effect is much smaller than the design recommendations used in the Czech Republic. The main parameters affecting the reduction ratio (ratio of buckling resistance of a column strengthened under load to the buckling resistance of a column strengthened without preloading) are the preload ratio and the column slenderness. Despite the high effect on the buckling resistance, the magnitude of initial bow imperfection and thickness of strengthening plates affected reduction ratio negligibly.

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