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Ultimate Load Capacity and Behavior of Thin-Walled Curved-Steel Square Struts, Subjected to Compressive Load

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ABSTRACT: There have been some experimental tests on hollow curved-steel struts with thin-walled square sections, in order to investigate their general behavior, particularly their capacity for bearing differing loads. One set of square tubes are cold-formed into segments of circular arcs with curvature radii, equal to 4000 mm. Different lengths of curved struts are fabricated so as to cover a practical range of slenderness ratios. The struts tests were pin-ended and had slenderness ratios, based on the straight length between ends ranging from 31-126. The cold-forming operation induces initial inelastic behavior and associated residual stresses. There is, therefore, an interaction among material effects, such as the strain hardening capacity, the Bauschinger effect, strain aging, and residual stresses, together with the significant geometrical effect of the initial curvature, caused by the cold-forming operation. Eventually the results from three series of tests, which are taken on fully-aged and stress-relief-annealed square curved struts, are compared. The variations in load carrying response are discussed.

Keywords: Bauschinger Effect, Curved Strut, Residual Stresses, Square Hollow Section, Strain Aging, Thin Walled, Ultimate Load Capacity.

INTRODUCTION

Thin-walled square-curved members are important components in spatial structures, such as roof structures and are also used in buildings with other architectural purposes. To have information on load-bearing capacity, inelastic behavior, and buckling performance of thin-walled square-curved members is essential for making a realistic assessment of their strength in steel structures. Formerly, in curved truss design, straight members were used predominantly between panel joints. This has now changed as curved members are commonly used; therefore, a clearer understanding is now required of curved members' behavior in order to build safe and economical structures.

The problems, affecting curved strut stability, are numerous and differing, owing to the range of variables such as initial radius of curvature, initial deflection at mid-height, slenderness ratio, and yield stress to

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name but a few. In addition to these effects the overall behavior of mild steel struts can be influenced by different material properties such as strain hardening, strain aging, and the Bauschinger effect.

Curved steel members with square cross-sections are often cold-formed during fabrication and may also undergo the same process during erection. The yield stress of the thin-walled square hollow curved steel struts can be decreased by loading-caused straining in the opposite direction from the initial straining, during the cold forming process (the Bauschinger effect). Consequently, the overall prior inelastic bending deformations can also cause a reduction in the buckling stress of mild steel, subjected to direct compression.

The present work follows some earlier investigations of strut behavior, wherein it was noted that the mentioned parameters (namely strain hardening, strain aging, residual stresses, and the Bauschinger effect) may have an influence on the performance.

Strain hardening is the term used to define the increase in strength as a result of increasing the strain, when the plastic deformation or flow occurs beyond the yield point (Raghavan, 2015). If unloading takes place in the inelastic range and is then followed by reloading, the selected path depends on the time since the unloading, itself, along with any likely temperature changes. The strength increase after reloading is a measure of strain aging (Rajan et al., 2011).

Whenever the direction of strain is reversed there may be a significant loss of yield strength, compared to the original value. This loss of yield strength is normally referred to as the Bauschinger effect (Hosford and Caddell, 2011).

The effect of aging on the mechanical properties of industrially-produced pipelines steel was investigated (Zhao et al., 2012). It was found that strain aging plays an important role in the tensile property and features of stress-strain curves, with the increase of either pre-strain or aging temperature, the strength increases while elongation decreases.

An experimental investigation on the manufactured steel circular tubes under concentric and eccentric axial loads was carried out (Linzell et al., 2003) to examine their behavior and ascertain the capacity of round tubular members, used in cross-frames of prototype curved steel bridge. The resultant data was utilized to compare experimental outcome and predicted capacities from AASHTO and AISC design specifications, in which both approximations and interactive concepts are used to quantify the behavior. Results from these comparisons indicated that measured ultimate loads were, in average, 1.3 times higher than values from factored AASHTO and AISC ultimate load predictions.

Gardner and Nethercot (2004) presented basic material properties (stress-strain and load-end shortening curves) for square, rectangular, and circular hollow specimens of stainless steel, suggesting modifications to the Ramberg-Osgood representation. They also developed an explicit relationship between cross-sectional slenderness and cross-sectional deformation capacity.

Afshan et al. (2013) developed suitable predictive models to determine the strength enhancements in cold-formed structures that arise during the manufacturing process. Zhao (2000) studied the section capacity of Very High Strength (V.H.S) circular tubes under compression. The Young's modulus of elasticity, tensile yield stress, and ultimate tensile strength were determined. It was demonstrated that, when applied to V.H.S circular tubes, the limits on local buckling in most existing design standards are conservative.

Jandera et al. (2008) discussed the influence of forming-induced residual stresses in stainless steel square hollow section on both material itself, and behavior of compressed members as well. The residual stress contribution to the stress-strain diagram concerning initial modulus of elasticity and non-linearity was shown by comparing as-received and stress-relieved material. It was shown that in some cases inclusion of residual stresses may lead to an increase in load load-bearing capacity.

Schmidt and Mortazavi (2007) have discussed the effects of strain reversal on steel tubular strut behavior. It was shown that strain reversal in inelastic range caused a dramatic drop in the tangent modulus for mild steel. The influence of other material properties was examined for steel tube. The variables chosen were

1. Strain hardening caused by varying the amount of tensile pre-strain,
2. Strain aging, and
3. The Bauschinger effect.

They concluded that tensile pre-strain reduces the tangent modulus, compared to the one found for the as-received steel tube, but strain aging was seen to be significant in reducing this loss in value. Strain aging is significant for rimming steels, less significant for semi-killed, and almost non-existent for fully-killed ones (Raghavan, 2015; Rajan et al., 2011).

Ghasemianet al. (1999) carried out experimental tests on hollow curved steel struts with circular cross-section in order to investigate their stability and general behavior. It was seen that the ultimate load capacity of Stress-Relief-Annealed (S.R.A) curved struts is reduced in comparison with the equivalent As-Received (A.R) ones. Also, it was observed that the Bauschinger effect is not significant for the curved struts with tested circular sections.

In the series of tests, reported herein, a sum of 24 curved square struts was tested including different material conditions: as-received, stress-relief annealed and fully aged. The squared hollow section test specimens underwent ERW (Electric Resistance Welding) manufacturing process. The initial radius of curvature was adopted as 4000 mm (Ghasemian et al., 1999) in order to investigate the effect of initial curvature radius, strain aging, residual stresses, and the Bauschinger effect on the ultimate load capacity.

Rezaiee-Pajandand Mohtashmi (2010) studied imperfect elements having initial curvature. They derived nonlinear tangent stiffness matrix of the beam-column, subjected to the axial force, nodal moments, and the lateral uniformly-distributed load. By using the proposed stiffness matrix, they were able to obtain load-displacement curve, finding good agreement between the proposed method and accurate plastic region methods in most cases.

Rezaie et al. (2015) carried out full scale load test of a horizontally curved steel box-girder element in order to detect structural defects. The member was tested under static and dynamic load so that the displacements, strains, and acceleration of different points of the member could be determined.

EXPERIMENTAL PROGRAM

There were some control tests for material behavior in tension and compression in order to provide basic data in elastic and inelastic ranges, including the influence of strain aging, residual stresses, and the Bauschinger effect. To determine the influence of the material effects on the ultimate load capacity and behavior of the thin-walled square-curved steel struts, a series of tests were taken under different conditions. These tests consisted of twenty four curved struts with curvature radii of 4000mm, which was based on the previous works on circular sections (Ghasemian et al., 1999).

The thin-walled square cross section, chosen for the study was 65 mm wide, with a wall thickness of 2.5 mm. A thin-walled square section was selected as a member, appropriate for using in space trusses. The square tube was produced by cold-forming and the seam was formed by the Electric Resistance Welding (E.R.W) process.

MATERIAL TESTS

Tests for material behavior in tension and compression were needed to furnish basic data in the elastic and inelastic range under forward and reverse loadings. The material used was a semi-killed mild steel with an intermediate propensity for strain aging (Raghavan, 2015; Rajan et al., 2011). The details of the tensile and squash tests on as-received square tube are summarized and listed in Tables 1 and 2.

Tensile specimens were tubes, 600 mm long (ASTM, 2000) and 12 mm thick in the end plates to provide grips for the testing machine. The squash tests were taken on lengths of 275 mm (three times outside diameter) (ASTM, 2000). The specimens were short enough to prevent any possibility of overall instability, influencing results.

Table 1. Tensile test results

Test No.	σ_y (MPa) Yield Stress	σ_u (MPa) Ultimate Strength	S.H.R (σ_u /σ_y)
1	337.7	380.6	1.13
2	336.1	381.5	1.13
3	336.0	379.7	1.13

S.H.R = Strain hardening ratio (σ_u /σ_y)

Table 2. Squash Tests on As-Received Square Tube.

Test No.	Yield Stress (MPa)	Unloading Stress (MPa)	Aging Treatment	Reloading Stress After Aging (MPa)	Strength Increase (%)
1	337.7	357.4	F.A	387.5	8.4
2	345.8	362.6	F.A	391.0	7.8
3	340.1	-	-	-	-
4	340.1	-	-	-	-
5	345.8	-	-	-	-

F.A = Fully aged for 2 hours at 100°C after unloading

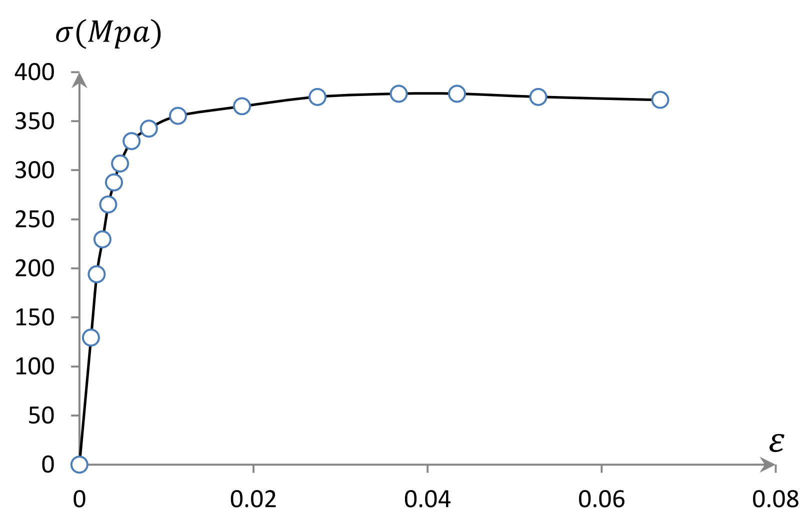

Fig. 1. Tensile stress-strain curve for as-received specimens

In addition to these compressive tests on the as-received square tube, some more were required to ascertain the influence of strain aging with respect to the Bauschinger effect. The fully-aged condition for these test specimens was attained by holding the specimens in an oven at 100°C for two hours. Prior tests had shown that such a period time was satisfactory for the specimens, used (Zhao et al., 2012). As a result, the square tubes were pre-strained in tension to a defined percentage elongation. The squash test specimens were performed on lengths of 275 mm, cut from the pre-strained tube in a tension up to 0.81%. The selected pre-strained value was calculated, using curvature-strain relation. Relation between the radius of the curvature (R), the curvature ($1/R$), and the strain within a curved member after rolling could be calculated as what follows:

$$\frac{1}{R} = \frac{\varepsilon}{y} \quad (1)$$

The strain (ε) is then given by the ratio y/R. The selected pre-strained value, related to the maximum strain in the extreme fibers of the square curved members after rolling to the radius of 4000 mm can be seen below (Figure 2).

Table 3 indicates the results for pre-strained square tube from comparative tests, devised to show the variations in the strength of the material, under different conditions. It was found that the Bauschinger effect (loss of material strength or modulus of elasticity on load reversal) cannot be completely isolated from the strength increase due to strain aging. The Bauschinger effect occurred in compression for all the tensile pre-strained, un-aged square tubes, and the Bauschinger effect was interactive with strain aging (Figure 3).

$$\varepsilon = \frac{y}{R} = \frac{32.5}{4000} = 0.81\%$$

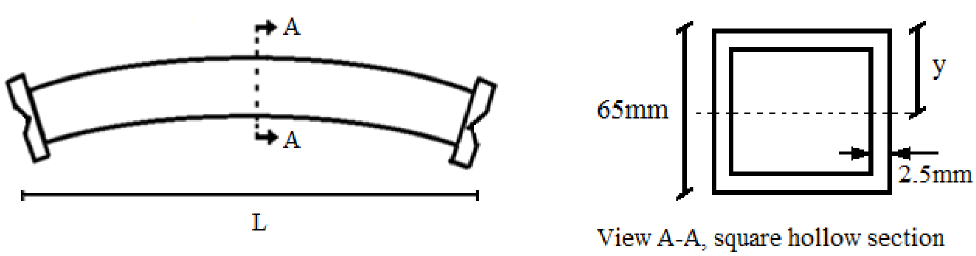

Fig. 2. Curved specimens

$\frac{1}{R} = \frac{\varepsilon}{y}$ (curvature − strain relation), for R = 4000 mm, $\varepsilon = \frac{y}{R} = \frac{32.5}{4000} = 0.81\%$

Table 3. Squash tests on pre-strained square tube

Test No.	Tensile Strain Before Unloading (%)	Condition	Yield Stress of Pre-strained Tube (0.2% offset) (MPa)
1	0.81	P.S+N.A	314.4
2	0.81	P.S+N.A	308.1
3	0.81	P.S+F.A	325.1
4	0.81	P.S+F.A	321.9

P.S = Pre-strained in tension by 0.81%
N.A = No strain aging
F.A = Fully strain aged (2 hours at 100°C)

Strain hardening of the E.R.W tube had relatively little influence on the Bauschinger loss, due to its low strain hardening capacity, having a strain hardening ratio of 1.13 (as the ratio of as - received ultimate to yield tensile stress).

When aging occurred after pre-straining in tension (2 hours at 100°C), the influence on the Bauschinger loss was clear. As the tensile pre-strain was applied (0.81%) with no strain aging, the compressive yield stress reduced (as measured by 0.2% offset) by 9.0% in comparison to the as received E.R.W tube, and 5.4% under a fully aged condition (Figure 3).

The stub column specimens were also Stress-Relief-Annealed (S.R.A) at 620°C for 30 minutes (Jandera et al., 2008). This process was adopted so as to relieve the residual stresses, set up during the square tube making process. Comparison of the stress-strain curve results from the as-received, as-received S.R.A and 0.81% pre-strained in tension, and then S.R.A squash tests, the very well-defined yield plateau of the S.R.A squash tests indicates that there were residual stresses, set up during the manufacturing process of the thin-walled square section. The averages of the clearly-defined yield stress of the as-received, as-received S.R.A, 0.81% S.R.A, and stub column tests were 341.9 Mpa, 299 MPa and 288 MPa respectively. Consequently, the stress-relief-annealing process lowered the yield stress of the specimens, compared with the yield stress of the as-received stub column tests (341.9 MPa). The prior tensile pre-straining almost had no effect on the stress-strain curves of the stress-relief-annealed square tube (Figure 3).

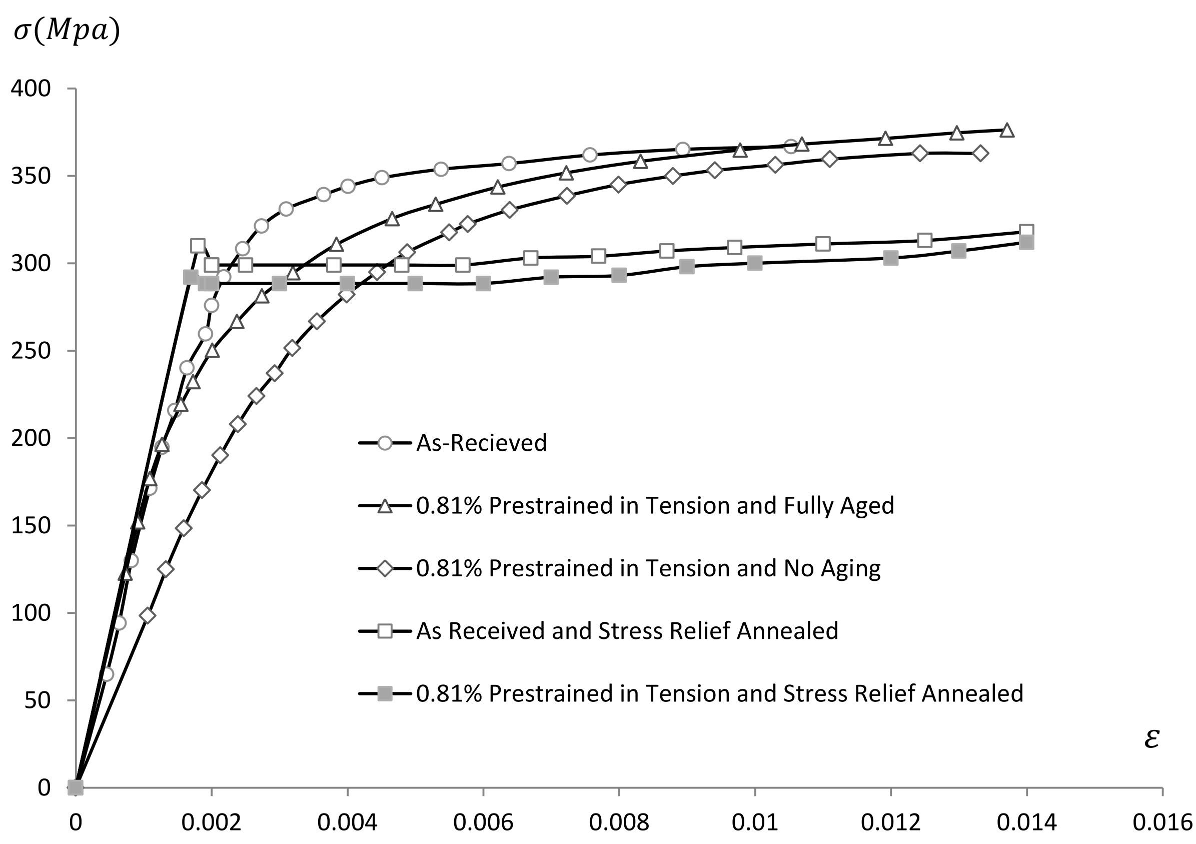

Fig. 3. Compressive stress-strain curves for all conditions

SQUARE HOLLOW CURVED STRUT TEST

In order to determine the influence of strain aging, the Bauschinger effect, and residual stresses on the ultimate load capacity and behavior of hollow curved steel pin ended square strut, a series of tests were done under different conditions. These tests consisted of twenty four curved struts with curvature radius equal to 4000 mm. The selected curvature radius for the curved strut tests was chosen as the possible curvature to be applied in space trusses and other roof structures (Ghasemian et al., 1999).

The slenderness ratios (*L/r*) of the 24 tested curved struts varied from 31-126. Figure 2 shows the lengths of the curved struts, measured between the two Knife edges. Also, Figure 4 shows a typical curved specimen prior to testing in the testing machine, while Figure 5 shows the curved specimen after failure.

Fig. 4. Curved specimen prior to testing

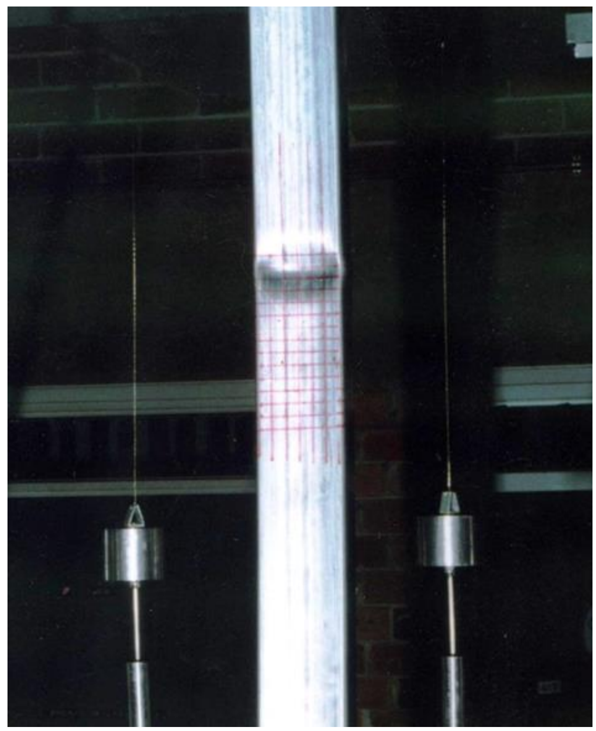

Fig. 5. Buckling mode of specimen

Fig. 6. Test set-up on the floor for long curved struts

In all of the tests a closed-loop servo-controlled testing machine was used in a controlled deformation mode.

Tests were taken at a controlled rate of ram travel, measuring 0.005 mm/sec. Because of a length limitation for testing the curved specimens in the servo-controlled testing machine, a simple frame was made on the floor to test the longer specimens (Figure 6). A 50 KN hydraulic jack was used for load application, being attached to a load cell to record the force level. The longer curved specimens were placed in a horizontal position on roller with the load being applied horizontally. Linear Variable Displacement Transducers (LVDT) was used to measure the end-shortening of each curved strut. The loads were applied in small increments. The ultimate load results of all E.R.W square curved struts with curvature radius, equal to R = 4000 mm, are presented in Table 4. A comparison will be made later on the difference in behavior and load-deflection plots and peak loads. Load-end shortening curves for as-received, fully-aged, and stress-relief-annealed E.R.W curved struts with a radius of 4000 mm with identical slenderness are shown in Figures 7-12 (the data are not available for S.R.A curved struts with *L/r* = 100, 126 except the ultimate loads). All curved steel struts failed in an overall instability buckling mode. Local buckling of the tube wall eventually occurred, regardless of slenderness ratios and material types (Figure 5).

Figure 13 gives the ultimate load capacities of the curved struts, the radius of which equals to 4000 mm, versus the slenderness ratio (*L/r*). The curved strut results of Figure 13 have been presented again in Figure 14, but in a normalized format. The curved strut critical stress was divided by the relevant yield stress, obtained from a stub column test. In this study a value of 0.2% offset strain was used to define the yield stress.

Table 4. Ultimate load capacity of square hollow curved steel struts with *R* = 4000 mm

Test No.	Condition	Length (mm)	*r* (mm)	*L/r*	P_{cr} (KN)
1	A.R	770	24.9398	31	131.30
2	A.R	766	24.9222	31	129.80
3	F.A	766	24.9480	31	125.80
4	S.R.A	766.5	24.9661	31	113.00
5	A.R	1174	24.9865	47	76.82
6	A.R	1172	24.9510	47	75.78
7	F.A	1176	24.8623	47	78.37
8	S.R.A	1178.5	24.9210	47	61.69
9	A.R	1561	23.8393	65	48.19
10	A.R	1557	24.8990	63	49.73
11	F.A	1560	25.0820	62	51.31
12	S.R.A	1558.5	24.8905	63	41.00
13	A.R	1759	24.9896	70	40.36
14	A.R	1759	23.7593	74	38.55
15	F.A	1758	24.9592	70	41.35
16	S.R.A	1756	24.9112	70	34.20
17	A.R	2362	23.6686	100	21.16
18	A.R	2365	24.9019	95	22.10
19	F.A	2360	24.9520	95	23.74
20	S.R.A	2358	24.9790	94	19.43
21	A.R	3130	24.8429	126	12.53
22	A.R	3130	24.9994	125	12.63
23	F.A	3130	24.8695	126	12.92
24	S.R.A	3127	24.7506	126	11.28

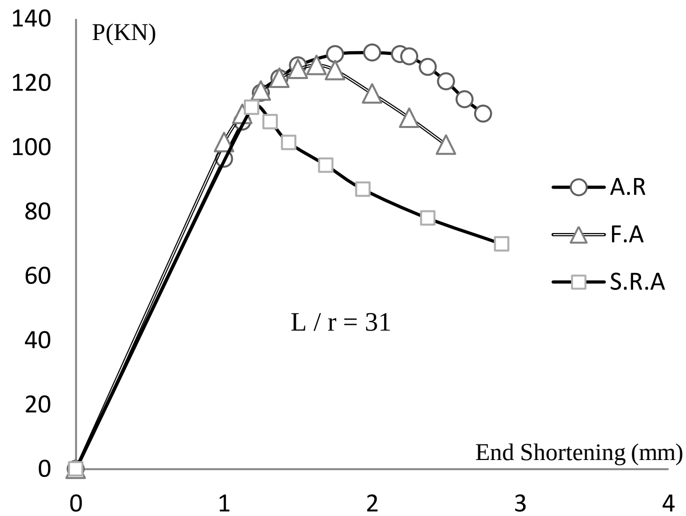

Fig. 7. Compressive load vs. end shortening, comparing all conditions

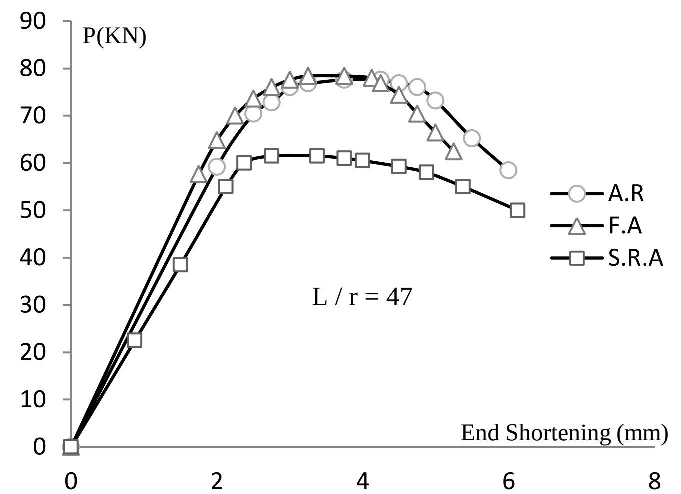

Fig. 8. Compressive load vs. end shortening, comparing all conditions

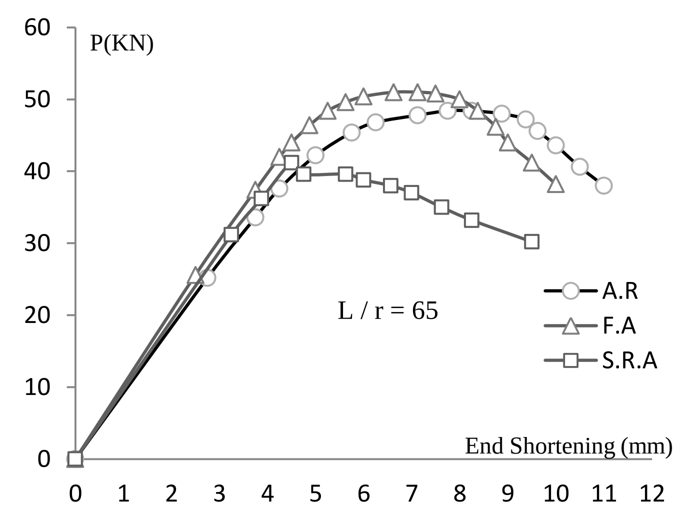

Fig. 9. Compressive load vs. end shortening, comparing all conditions

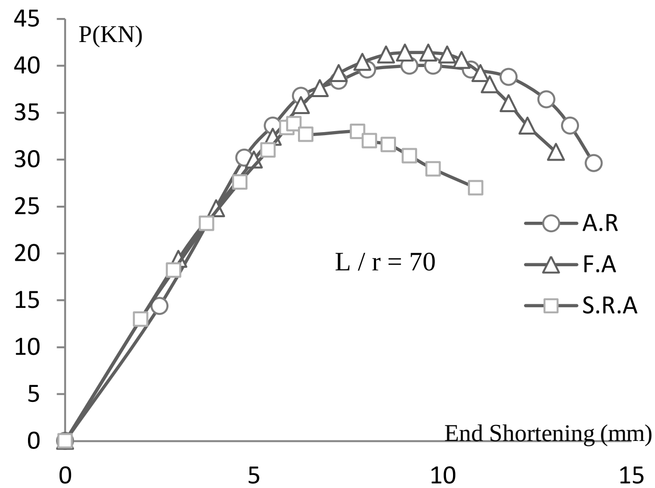

Fig. 10. Compressive load vs. end shortening, comparing all conditions

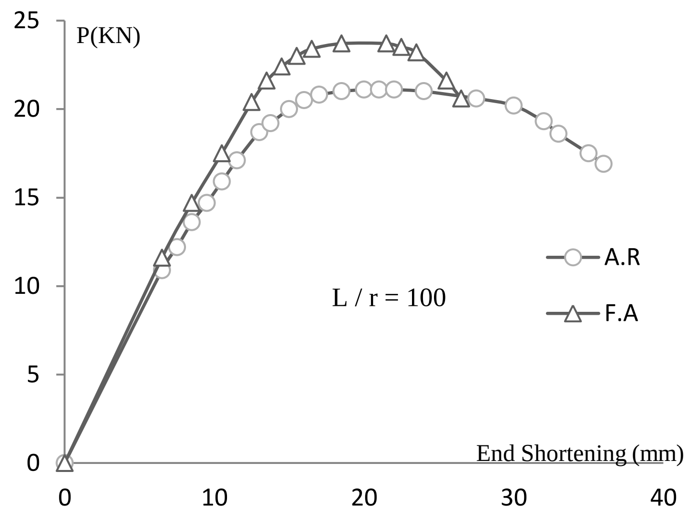

Fig. 11. Compressive load vs. end shortening, comparing all conditions

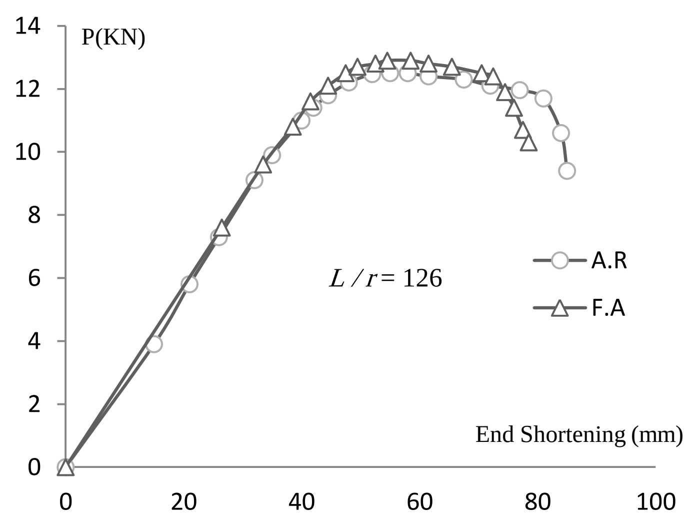

Fig. 12. Compressive load vs. end shortening, comparing all conditions

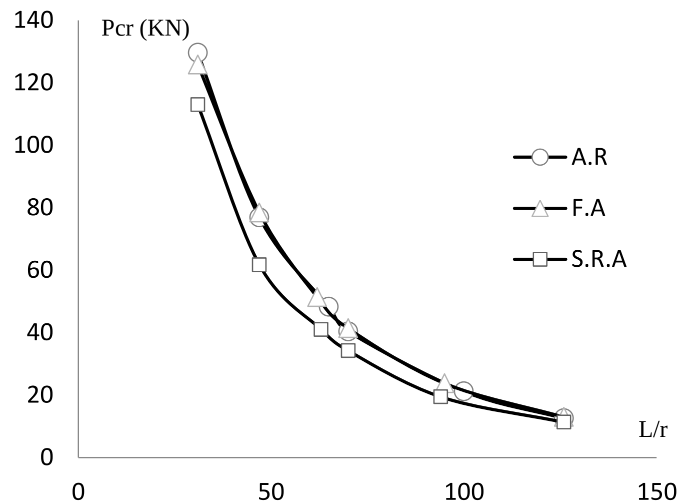

Fig. 13. Load capacity vs. *L/r*, comparing all conditions

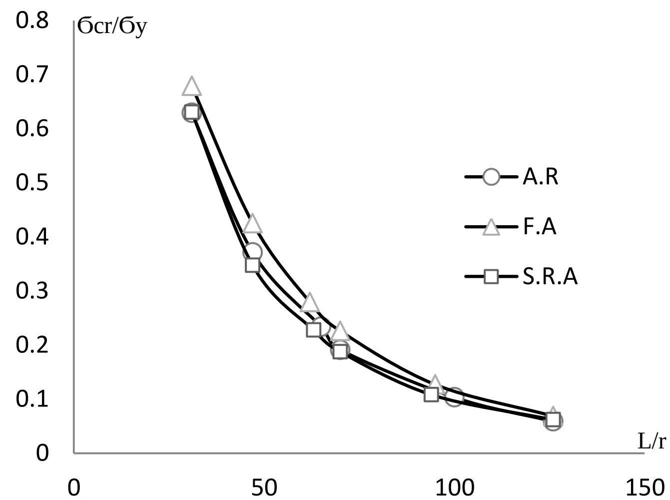

Fig. 14. Normalized critical stress vs. *L/r*, comparing all conditions

DISCUSSING THETEST RESULTS

The primary objective of this study was to obtain the ultimate load capacities of pin-ended hollow curved tubular struts with square cross-section, subjected to axial load for different material conditions (as received, fully- aged, stress- relief-annealed). As seen from Table 4, the peak load decreases as the length of the specimens increases. Decrease in the peak load can be attributed to the increasing initial deflection with increasing slenderness of the curved struts. From Figure 13 no increase in the ultimate load capacity of curved struts is observed due to aging, in the range of slenderness ratios 31-126. The influence of strain aging on the ultimate load capacity does not change with slenderness ratio (*L/r*). As aforementioned, the steel type used was semi-killed one which displayed an intermediate tendency to strain age.

In comparison with as–received curved struts, the ultimate load capacities are reduced up to 19% for stress-relief-annealed curved struts with a curvature radius of 4000 mm. The reduction in the ultimate load capacity of stress-relief-annealed curved struts was due to the drop in the yield stress after the annealing process, though the curved struts were free of any residual stress, induced during the curved tube manufacturing process.

As different material types are used (as-received, fully-aged, stress-relief-annealed), a comparison in a normalized format is more reasonable. As shown in Figure 14, for the steel used, the differences are insignificant between the curves for the as-received and fully-aged curved struts for 4000 mm radius of curvature.

A yardstick, by which the influence of the Bauschinger effect can be measured, is to compare the ultimate normalized load capacities of the curved struts in both the Stress-Relief-Annealed (S.R.A, free of residual stresses) and the as-received conditions. As the test results of the normalized ultimate load capacities of the as-received curved struts lie above the as-received S.R.A curved struts (Figure 14), it appears that the Bauschinger effect is not significant for the in-elastically curved struts with the radius of curvature, adopted for testing (R = 4000 mm).

The reason behind this is that when a curved strut is under axial compressive loading, the Bauschinger effect occurs at that part of the cross-section where the tensile inelastic curving pre-strains had happened, whereas the other part of the cross-section in which the compressive curving pre-strains have occurred will experience the influence of strain hardening, which compensates for the Bauschinger effect.

It should be noted that the results, obtained for curved struts with square cross-sections, are similar to the previous results of curved struts with circular sections (Ghasemian et al., 1999). For both square and circular sections, the ultimate load capacity of curved struts is reduced due to annealing process (19% for square and 16% for circular sections); however, the increase in the ultimate load capacity due to strain aging and the Bauschinger effect are not significant.

CONCLUSIONS

In order to investigate the general behavior of square hollow curved steel struts, subjected to compressive load, 24 specimens (12 A.R, 6 F.A, and 6 S.R.A) were tested as pin-ended struts. The slenderness ratios, based on the straight length between pin ends, varied between 31 and 126.

On the basis of the curved strut tests, taken herein, the following conclusions can be drawn:

It appears that the Bauschinger loss (reduction in the ultimate load capacity) due to flexural pre-straining was not significant for the curved struts with curvature radius equal to 4000 mm, as the normalized curves of the stress-relief-annealed curved struts are below the as-received curved struts with curvature radius, measuring 4000 mm.

The reported test results show that no increase in axial load capacity is obtained due to strain aging for the type of steel used, which displayed an intermediate tendency for strain aging.

The stress-relief-annealing process reduced the absolute ultimate load capacity of curved struts (up to 19%), even though the curved struts were then free of residual stresses, and the reduction occurred because of the reduction in the yield point due to the annealing process.

The ultimate load capacity of such struts significantly decreased as initial deflection rose at mid-height and slenderness ratio. In all cases the peak load decreased as the slenderness of the specimens increased.

To obtain a better understanding of the influence of the Strain Hardening Ratio (S.H.R) on the ultimate load capacity of curved struts, further tests with higher strain hardening ratios are necessary.

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