Residual stresses in cold bent HE 100A steel arches

R.C. Spoorenberg[1,2], H.H. Snijder[2], J.C.D. Hoenderkamp[2], M.C.M. Bakker[2]
[1]*Material Innovation Institute, M2i, Delft, Netherlands*

[2]*Eindhoven University of Technology, Department of Architecture, Building & Planning, Eindhoven, Netherlands*

Arches are structural elements applied in roofings and bridges. They may be formed by cold bending of hot-rolled wide flange sections. The original residual stress pattern due to differential cooling in the wide flange section is altered as a result of cold bending. Residual stresses resulting from differential cooling in straight I-sections have been well documented; however, this is not the case for residual stress patterns resulting from cold bending. Residual stresses can have a significant influence on the strength and stability of arches. This paper presents experimentally measured residual stresses and a finite-element-based method for obtaining residual stresses, in cold-bent arches consisting of HE 100A wide flange sections. Residual stresses in cold bent specimens were measured with the sectioning method. A finite element model has been implemented using ANSYS 11.0. The residual stresses obtained from numerical analyses and actual measurements on cold bent steel arches do not only differ from typical hot-rolled residual stress patterns but also deviate from earlier proposed cold formed stress distributions. The results obtained from the finite element method show moderate to good agreement with experimental results.

1 INTRODUCTION

In structural steel members, residual stresses exist due to two major causes: uneven cooling due to hot-rolling and cold forming. Straight hot rolled sections contain residual stresses due to uneven cooling. When these sections are cold bent into an arch shape, the original residual pattern will change due to cold forming. This paper focuses on residual stresses resulting from cold-bending of hot-rolled beams. A theoretical model for the development of residual stresses for cold bent beams was first suggested by Timoshenko (1940) based on a bi-linear material law, assuming that the curvature was obtained by the application of a uniform bending moment (Figure 1). The calculated residual stresses were the result of a summation of loading and unloading stresses. The same residual stress pattern was adopted by King & Brown (2001). Residual stresses were measured by Weng & White (1990) on press braked plates. They found a residual stress pattern quite similar to the suggested residual stress patterns by Timoshenko. Roller bending is a well-known process to manufacture circular or more complex shaped arches from straight beams. Numerous investigators have studied the roller bending process for beams with a square cross section and flat plates, by considering the relationship between the movement of the rollers and the emerging permanent curvature: Hansen & Jannerup (1979), Yang & Shima (1988), Gandhi & Raval (2008), or by analyzing shape tolerances in finished plates, Zeng et al. (2008). Residual stresses in cold-drawn tubes were examined numerically by Welo et al. (1994). Numerical simulations of production bending of aluminum extrusions were performed by Paulsen & Welo (1996). Research on residual stresses in cold bent I-sections has been undertaken at Eindhoven University of Technology where La Poutre (2004) measured residual stresses in cold bent arches by employing the hole-drilling method; however

large scatter in data was found. Spoorenberg et al. (2008) suggested a simplified numerical model to simulate the roller bending process, based on the assumption of Timoshenko's theoretical model. Comparison between numerical and experimental results revealed that further enhancement of the numerical model is required. To the authors' knowledge no further research has been undertaken to investigate residual stresses in cold bent I-shaped sections, numerical or experimental. It is expected that a simplified residual stress distribution as shown in Figure 1 cannot be adopted since the true roller bending process exhibits a complex interaction between rollers and the beam.

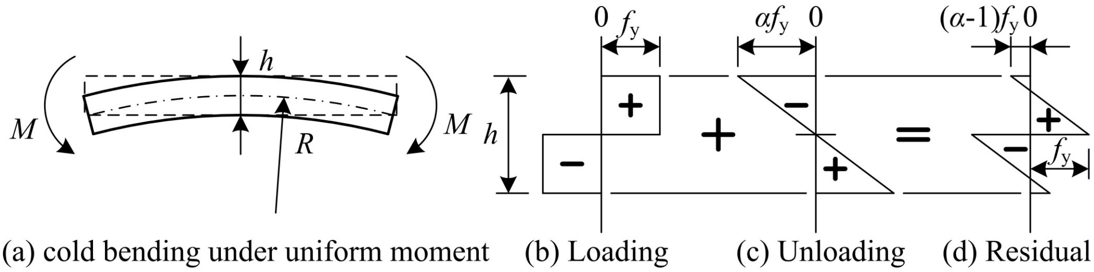

Figure 1. Simplified theory on residual stresses in cold bending by Timoshenko (1940). α denotes the ratio between the plastic and elastic section modulus, f_y is the yield stress, h is the height of cross section, R the radius of the circular arch.

In section 2 an outline of the roller bending process is given. The experiments as conducted on cold-bent sections are presented in section 3. Also the methodology of the experiments and underlying assumptions are given. In section 4 the numerical model is presented. The results of the experiments and numerical simulations are presented in section 5 and discussed in section 6. The paper ends with conclusions in section 7.

2 FABRICATION PROCESS OF COLD-BENT SECTIONS

A three-point roller bending machine was used to manufacture steel arches. The steel arches were bent into a circular shape with a prescribed radius on a Roundo machine, named after the Swedish company. A schematic representation of the machine is given below (Figure 2). The machine consists of three large rollers with a diameter of 0.6 m and a small flange support roller (Figure 2a). Cold-bending is achieved when the member passes through the set of rollers. The right roller moves towards the center roller according a fixed path (Figure 2b) and subsequently all rollers rotate (Figure 2c). The flange support rollers on either side of the tension flange exert a force on the flange thereby preventing web crippling. Depending on the desired radius, the shape is passed through the machine in repeated passes. A skilled workman can attain an accuracy of 2-3 mm for the desired radius with this machine. The ends of the beam do not have the desired radius due to placement requirements and therefore have to be considered as waste material (Figure 2c). A more extensive description of the roller bending process has been given by Bjorhovde (2006).

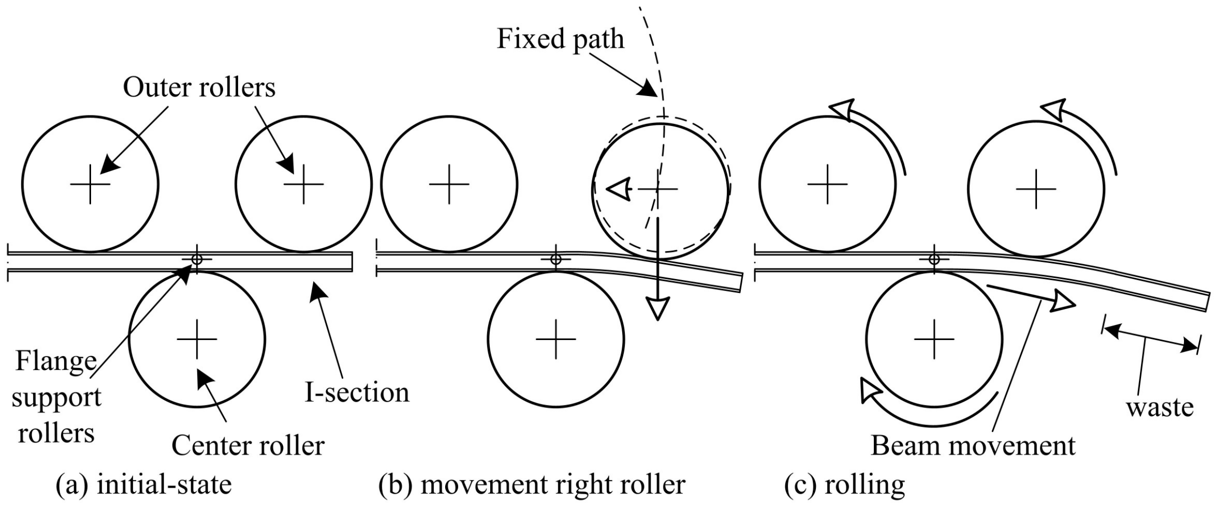

Figure 2. Top view of the roller bending process

3 EXPERIMENTS

3.1 *Experimental investigation*

The experimental programme comprised residual stress measurements on 3 curved HE 100A sections. All tested material was grade S235 mild steel. Each section was bent into a different curvature, which represents a circular arch with a different bending radius. An outline of the experimental plan is presented below in Table 1. Additional tests on straight reference I-sections were carried out to determine the mechanical properties of the base material.

Table 1 Experimental plan

Specimen no.	Bending radius [mm]
1	1910
2	2546
3	3820

3.2 *Measurements*

The sectioning method was used to measure residual stresses in cold-bent steel arches. The test specimen was saw-cut from larger steel arches. Electrical strain gauges were applied to the surface of the cold bent I-sections. Electrical strain gauges were selected in preference to a mechanical gauge or Whittemore gauge due to their accuracy and applicability to curved steel. For this investigation small (2 x 6 mm) electric strain gauges manufactured by Tokyo Sokki Kankyujo Co. Ltd. were used. The arrangement of the electrical strain gauges is shown in Figure 3. To reduce end effects, the test area was a distance of 2.5 times the flange width of the beam from the ends. The dashed lines indicate the saw cuts. A total number of 40 electric strain gauges per specimen were applied, resulting in a total of 120 for the entire experimental programme. Only the longitudinal stresses were measured.

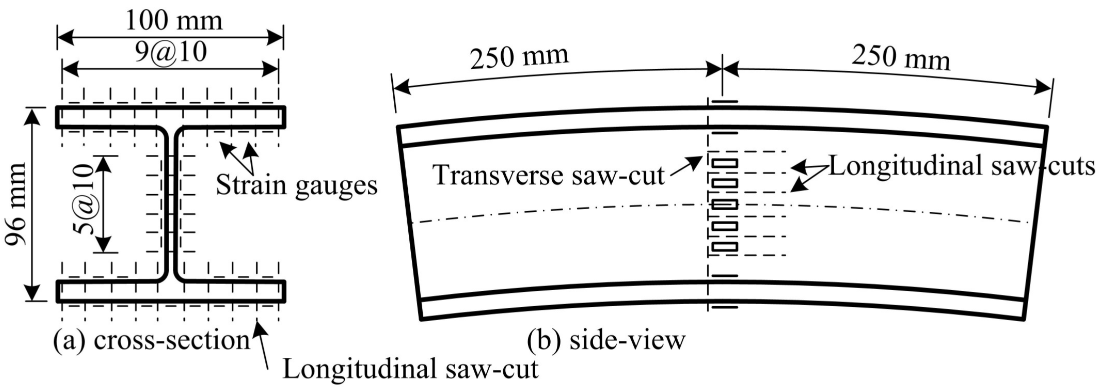

Figure 3. Strain gauge positions for the sectioning method

The specimen was clamped in a vise and the transverse saw cut and subsequent longitudinal saw cuts were made with an electrical band saw and hand saw respectively. The influence of heat release of the electrical saw-cuts was suppressed by supplying fluid coolant. Short-circuiting of the electrical strain gauges was prevented by covering the gauges with a protective layer. Strain release was recorded during the entire saw-cutting procedure. The final strains were recorded approximately 30 minutes after the end of the saw-cutting. The residual stresses were determined by converting the residual strains using Hooke's law, thereby assuming elastic release of the strains. Taken that the residual stress distribution can be modeled as linearly varying through the material thickness a distinction was made between membrane and bending strains. The membrane strains are the average of the measurements of two gauges on either side of the flange or web.

4 FINITE ELEMENT MODEL

The finite element code ANSYS 11.0 was used to simulate the cold bending process (Figure 4). Only one half of the I-section was modeled, using symmetry to reduce computation time. Geometri-

cal and material non-linearities and contact were considered. Preliminary trials on modeling the wide-flange section by means of shell or beam elements gave unacceptable results. Therefore the roller bending process was modeled using a SOLID95 element which is a 3-D, 20-node element with reduced integration. This brick element has large rotation, large strain and plasticity capabilities. Two brick elements were used through the thickness of the flange and a total of 6 brick elements were used along the half flange width. The half-web thickness was modeled by one brick element and 14 brick elements were applied along the height (Figure 5). The interaction between the steel section and the rollers was simulated by contact elements.

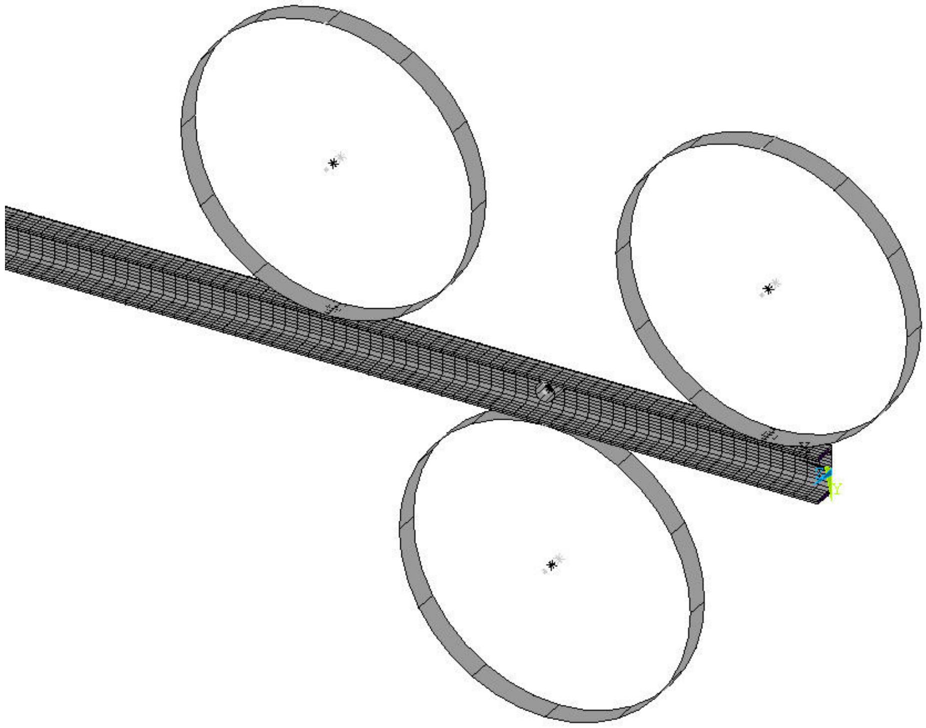

Figure 4. Numerical model

The material behavior was modeled using a true stress-logarithmic strain relationship based on tensile test data of the straight base material. The material plasticity was characterized by the Von Mises yield criterion, the Prandtl-Reuss flow rule and the isotropic hardening law. The adopted material law obtained by uniaxial tensile tests is presented in Figure 6. Experimental tensile-test data showed a significant difference between the mechanical properties of coupons taken from just underneath the web-flange junctions and other locations. This is taken into account in the numerical model (Figure 5c). The stress-strain characteristics were obtained from the waste material of the arch forming process. No initial residual stress distribution due to differential cooling was applied to the straight beam in the model since it is assumed that these stresses have no influence on the final residual stress distribution.

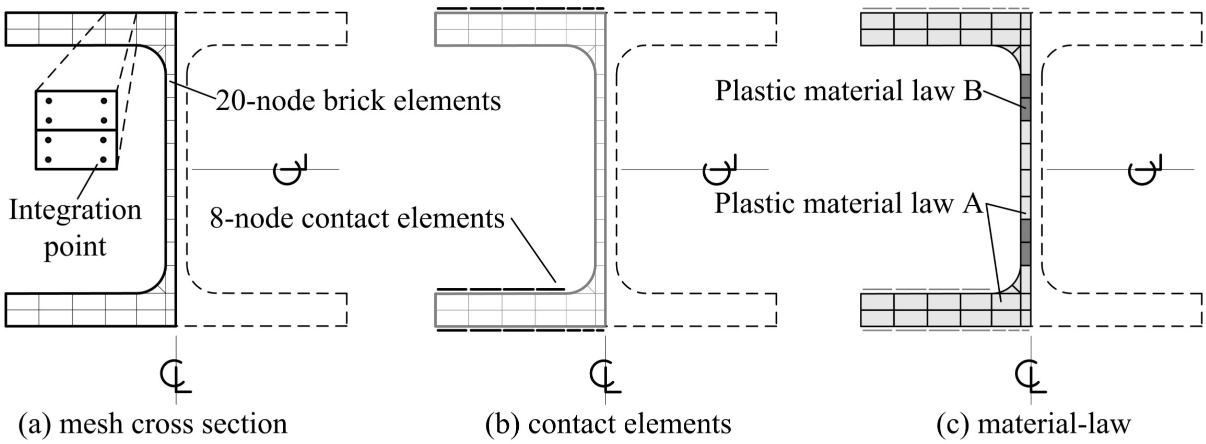

Figure 5. Cross-sectional mesh

The non-linear equilibrium equations were solved iteratively by the Newton-Raphson solution algorithm. The equations were considered solved and iterations were stopped when the residual or out-of-balance forces, displacements and rotations were below 0.05 % of the applied forces, displacements and rotations. A total of 64 load steps was employed in order to model the roller bending process. Permanent curvature in the beam was achieved by moving the right roller towards the center roller and feeding the beam through the rollers. Only a single pass was simulated, assuming that the residual stresses are the same for single and multiple pass bending. The feeding process was modeled by rotating the center roller and applying an artificially high friction coefficient between the center roller and the outside of the compression flange (i.e. the flange which is subjected to compressive strains). The contact interaction between the other flanges and rollers was assumed frictionless. The radius after spri ngback or elastic release was obtained by reviewing the total strains (= elastic strains + plastic strains) in the cross section. A linear total strain distribution along the height was observed for the strains parallel to the beam axis. This made it possible to obtain the curvature by reviewing the strains.

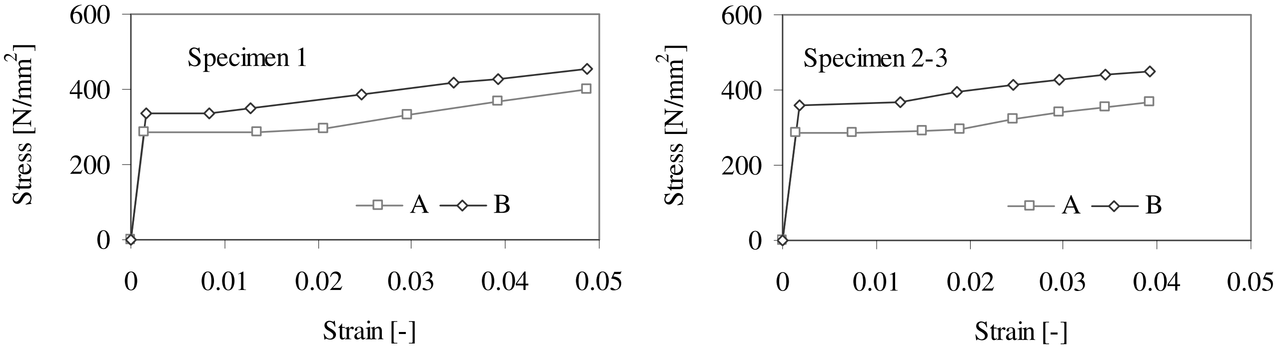

Figure 6. Stress-strain behavior of base material locations indicated in Figure 5

5 RESULTS

An overview of the total output of the numerical model is given and subsequently the residual stresses are presented. Figure 7 shows the curvature distribution along the beam length. It can be seen that, when moving from right to left, after an initial transient phase a constant curvature distribution is found, indicating uniform curvature and hence a circular arch. The small peak at the end (between 0 and 1000 mm) is due to roller pressure on the beam. The difference between the curvature at this peak after the transient phase and the uniform curvature is the elastic release or so-called springback. Since it is impossible to obtain the exact prescribed radius of the specimen, the arch was modeled with both a smaller and a larger radius than that of the radius of the specimen. It was found that the results of the analyses are not very sensitive to the radius, thus a closer approximation of the true radius is not necessary. The residual stresses in the numerical model are evaluated at a distance of 1.3 m from the left end of the arch in order to obtain a good representation.

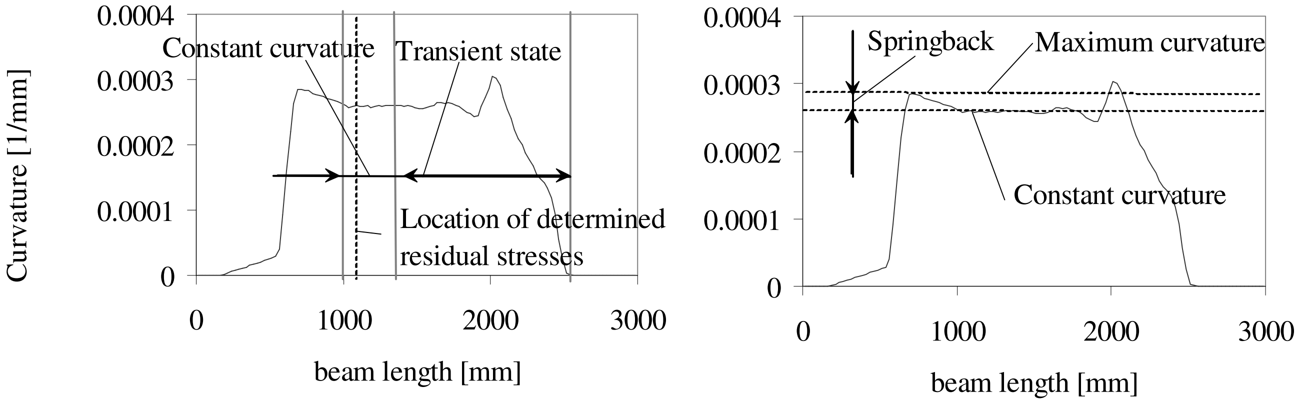

Figure 7. Curvature distribution along beam length.

The Figures 8-10 show the results of the measured residual stresses, numerically obtained values and the theoretical distribution along the flange width and web height. The experimental results are the average of the measurements at the out- and inside of the flanges and left and right side of the web. Due to the position of the fillets and web no average residual stress values could be obtained at the web-flange junction. The tensile stresses and compressive stresses are denoted positive and negative respectively.

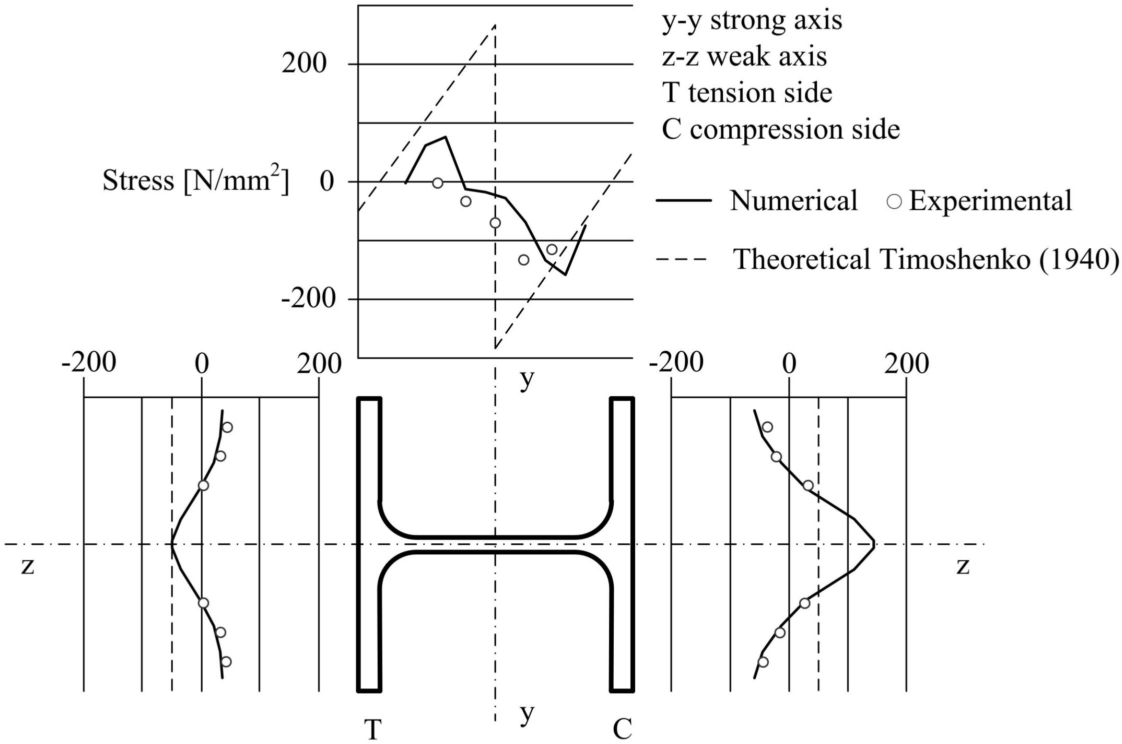

Figure 8. Average residual stresses specimen 1 (R=1910 mm)

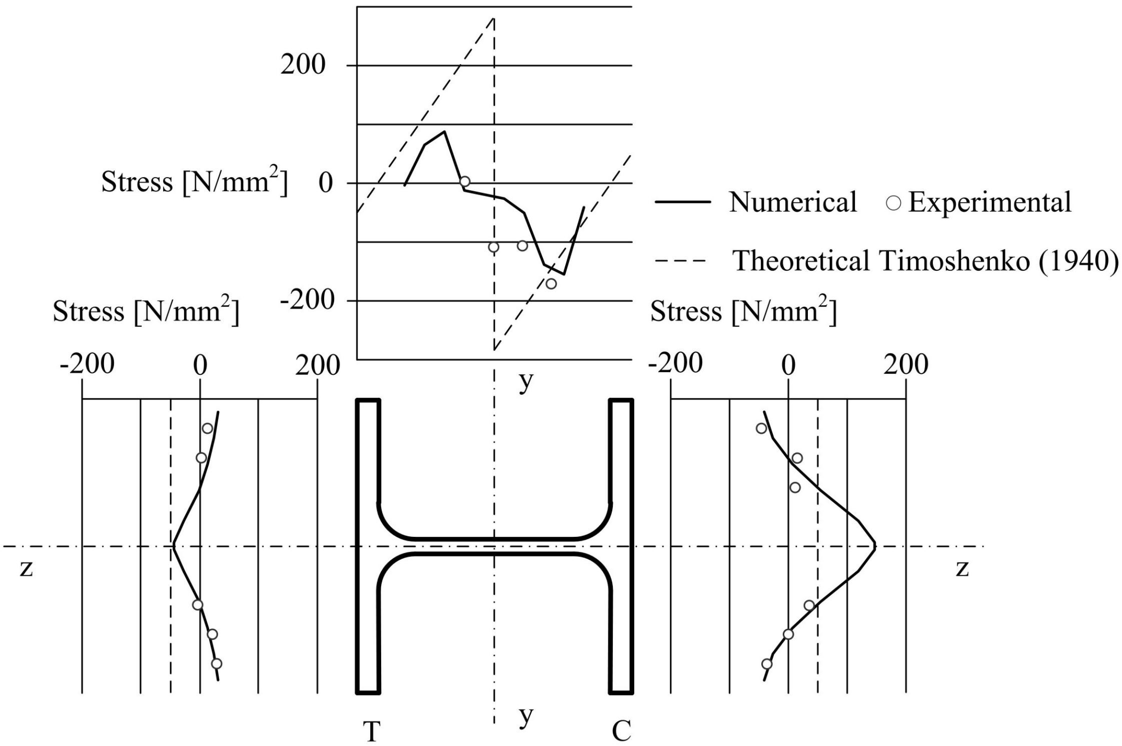

Figure 9. Average residual stresses specimen 2 (R=2546 mm)

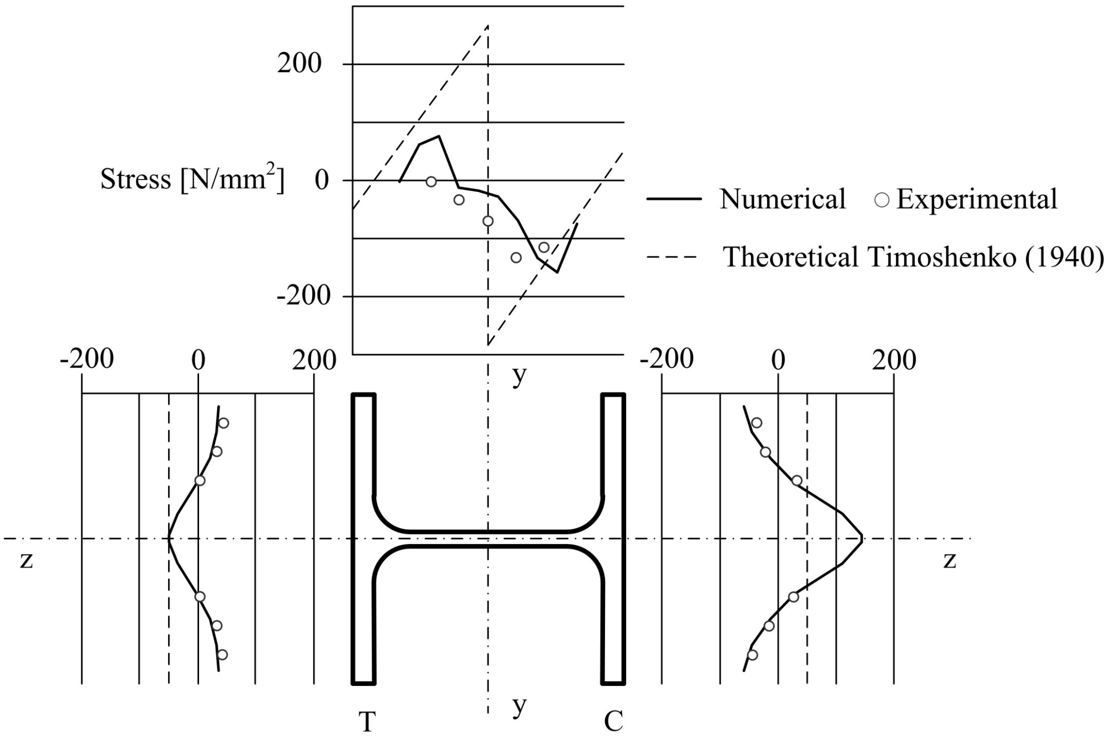

Figure 10. Average residual stresses specimen 3 (R=3820 mm)

6 DISCUSSION

The residual stress distributions shown in Figures 8-10 reveal the following characteristics. The measured residual stresses are symmetric around the z-axis justifying the numerical simplification to model only one half of the I-section. In the compression flange (denoted by C) which is compressed during the roller bending process, large tensile residual stresses are found at the web-flange junction in the numerical analysis, while the flange tips show compressive residual stress. The opposite occurs at the tension flange (denoted by T), which is elongated during the roller bending process, although the stresses are lower. The web-flange junction is under compressive stress and the flange tips experience tensile stress. The web is predominantly subjected to compressive residual stress, which increase towards the compressive flange. The numerical results show good agreement with experimental data for the flanges, although less coherence is found in the web. The differences between experimental/numerical results and the theoretical solution indicate that a multi-axial stress state is present during the roller bending process which is not accounted for in the theoretical solution. Unlike the theoretical residual stress pattern as suggested by Timoshenko, the obtained numerical and experimental patterns are not antisymmetric with respect to the y-axis. A large theoretical stress reversal in the web is not observed in both the simulations and experiments. Both the numerical and experimental results show that no clear relation exists between the amount of curvature and residual stress level. The experiments and numerical simulations yield larger residual stresses compared to measured residual stresses due to uneven cooling in identical straight sections Daddi & Mazzolani (1971), Mazzolani (1975).

7 CONCLUSIONS

Experimental and numerical residual stress distributions have been obtained for a total of three cold bent grade S235 HE 100A sections. A computer model was created with the finite element code ANSYS 11.0 to predict residual stress distributions. Geometrical and material non-linear analyses with contact elements have been performed to simulate the roller bending process. The sectioning method was employed to measure the residual stresses. Moderate to good agreement between numerical results and laboratory measurements was found. Both the experimental and the numerical results shows patterns which differ from theoretical models suggested earlier and from residual stress patterns due to uneven cooling in straight hot rolled I-sections. Large tensile stresses were ob-

served at the web flange junction of the compression flange. The region of the web close to the compressed flange showed larger compressive residual stresses. Further research is under way to investigate the residual stress pattern for steel grade S355 and other sections by adopting both a numerical and experimental approach.

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