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RESIDUAL STRESS MEASUREMENTS IN ROLLER BENT HE 100B SECTIONS

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Abstract. *This paper presents residual stress distributions in roller bent wide flange HE 100B sections obtained from experiments. The wide flange steel beams are curved at ambient temperature by means of the roller bending process, which alters the initial residual stress pattern. Curved wide flange steel sections are frequently used in large span structures like roofings and bridges. Their geometry and loading often make these arches susceptible to instability phenomena's. An accurate knowledge of the residual stresses is therefore necessary. An experimental program was set up to investigate the residual stresses in roller bent sections. Measurements were carried out on straight and curved sections. It was found that the residual stresses in roller bent sections differ significantly from those in their straight counterparts.*

1 INTRODUCTION

A structural steel section contains residual stresses which are a result of the manufacturing process. Residual stresses are in general of primary importance for structures susceptible to loss of stability, since the presence of these stresses causes early yielding and thereby a reduction in load carrying capacity.

Extensive research has been carried out on the measurements of residual stresses in straight hot rolled sections, [1], [2], [3] and [4] amongst others. Results were summarized and published in various forms [5], [6] and [7]. It was found that residual stresses in straight hot-rolled sections are characterized by compressive stresses in the flange tips and tension in the web-flange junction. The web can be either under compressive or tensile residual stress depending on the shape of the cross-section.

Cold forming structural steel at ambient temperature changes the residual stress pattern due to plastic strains. This characteristic of cold forming was first observed in [8] where the residual stress distribution in cold-formed circular hollow sections was investigated. Residual stresses in press-braked plates were measured in [9], [10]. The residual stresses in bent sheet metals were reported in [11].

Theoretical models are available to obtain a residual stress distribution in cold-bent sections. A first solution was proposed in [12] for bars under uniform bending based on elastic perfectly-plastic material behavior. The basic theory is illustrated in Figure 1, where α=ratio between the plastic and elastic section modulus or shape factor, f_y=yield stress, h=height of the cross section and R=radius of the circular arch. When a stress free bar or plate is plastically bent into a specific radius, a plastic stress distribution emerges (Figure 1(b)). After releasing the acting moments, an elastic release or springback of the member takes place, thereby imposing an elastic stress distribution on the already present loading stresses (Figure 1(c)). The result is a stress distribution, which is a summation of the loading and unloading stresses (Figure 1(d)) thereby assuming a uniaxial stress condition. The theoretical model has found widespread application in structural analysis of curved steel, as reported in [13].

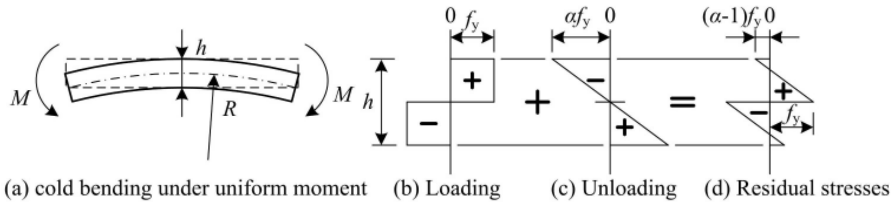

Figure 1 Simplified theory on residual stresses due to cold bending.

This theoretical model has been used to find residual stresses in roller bent sections. However the model is questionable since the true bending process features a complex interaction between rollers and beam which cannot be represented by a uniaxial loading-unloading procedure. At Eindhoven University of Technology an experimental and numerical investigation has been started to study the roller bending process and its effects on wide flange steel beams. This project includes a variety of wide flange sections and different steel grades. Some of the experimental results have been published in [14].

A short description of the roller bending process is presented in section 2. The experimental program and test setup are given in section 3. In section 4 the results of the residual stress measurements as taken from both straight reference sections and roller bent sections are presented. Section 5 discusses the results of the measurements and the paper ends with conclusions in section 6.

2 ROLLER BENDING PROCESS

Roller bending is a manufacturing technique whereby a straight wide flange section is shaped into a curved one by feeding it through a roller bending machine. The roller bending machine can be equipped with either three or four rollers. This study is confined to the first type. Because of the three rollers' pyramid arrangement, roller bending is sometimes referred to as 'pyramid rolling' (see Figure 2).

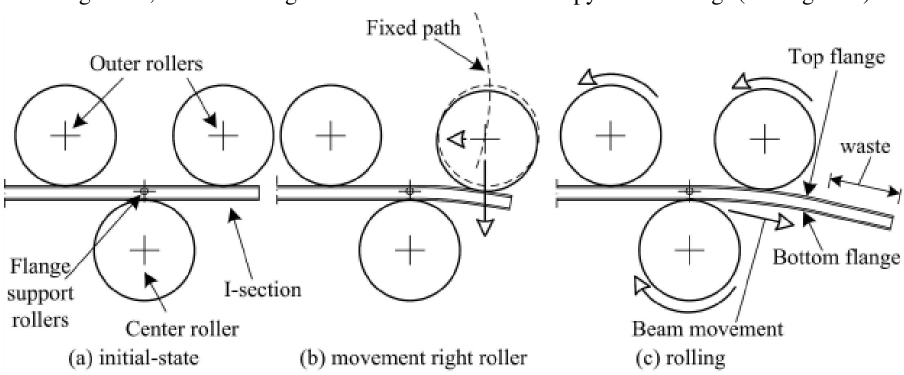

Figure 2 Roller bending process

A straight member is placed in the machine (Figure 2(a)) and successive rolling and movement of the rolls induces permanent curvature of the sections (Figures 2(b) and (c)). The top flange and bottom flange are elongated and shortened respectively. The roller bending process is mainly featured by continuously changing bending-type deformations as the section moves through the rollers. During the bending process all three rollers are driven and automatic speed compensation is implemented for the difference in surface speeds between the inner and outer circumference of the section being rolled. Depending on the machine type, sections with a height of up to 1 m can be bent. Several additional passes are required until the designated radius is attained. Steel members can be bent the easy way or the hard way which involves bending about its weak axis or about its strong axis respectively. When bent the hard way, a small roller is placed at the inside of the top flange to prevent web crippling. This investigation is limited to wide flange sections bent about the strong axis. Although complex curvatures are possible, this study is confined to beams bent into a circular shape. Due to placement requirements within the bending machine, it is impossible to impose a permanent curvature along the complete length of the beam. The ends remain straight and have to be considered as waste material (Figure 2(c)). A more extensive description of the roller bending process is reported in [15].

3 EXPERIMENTAL TEST SETUP

3.1 Experimental Plan

The complete experimental program is presented in Table 1. It comprises commercially available hot-rolled wide flange steel sections bent into different radii and with different steel grades. A full overview on the HE 100B profiles which will be presented in this paper is given in Table 2.

Table 1: Total experimental plan

Section	Steel Grade	Bending Radius [mm]
HE 100A[1] HE 100B	S235, S355	1910, 2546, 3820
HE 360B[1]	S235, S355	8000
IPE 360[1]	S235, S355	4500, 8000

[1] Published in [14]

The initial residual stress distribution was determined from straight reference sections from which the curved ones were made. Tensile tests were carried out on coupons taken from the flange of the straight and curved members in order to assess the increase in yield stress and ultimate tensile stress as a result of the roller bending process (Figure 3).

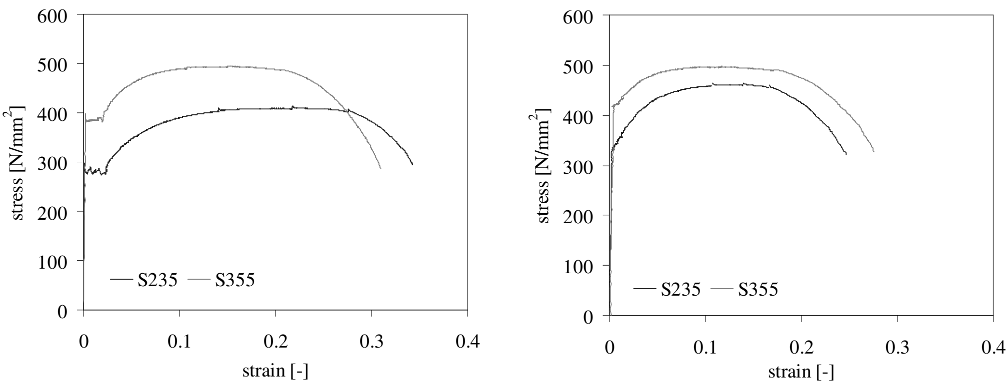

Figure 3. Stress strain relationship for HE 100B with steel grade S235 and S355, straight reference section (left) and roller bent section with a radius of 2546 mm (right).

Table 2: Experimental plan

Specimen no.	Steel grade	Section	Radius [mm]	Measured yield stress of straight reference sections [N/mm^2]
1	S235	HE 100B	1910	248
2			2546	285
3			3820	
4	S355		1910	386
5			2546	390
6			3820	

3.2 Preparation

The sectioning method was used to measure residual stresses in roller bent steel arches. The test specimen was saw cut from larger steel arches. Electrical strain gauges were applied to the surface of the roller bent wide flange sections. For this investigation small (2 x 6 mm) electric strain gauges manufactured by Tokyo Sokki Kankyujo Co. Ltd. were used. The arrangement of the strain gauges is shown in Figure 4(a). To reduce end effects, the test area was a distance of 2.5 times the height of the beam from the ends (Figure 4(b)). Only longitudinal stresses were measured.

A transverse saw cut and subsequent longitudinal saw cuts were made with an electrical band saw and hand saw respectively. The influence of heat release from the electrical band 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 of paraffin. Strain release was recorded during the entire saw cutting procedure. Strain measurements were recorded until approximately 30 minutes after the end of the cutting. Strain measurements were converted into stress values by multiplying the strain by the Young's modulus as obtained from the tensile tests on the straight reference sections, thereby assuming elastic release of the strains. Stress values on opposite sides of the flanges and webs were averaged.

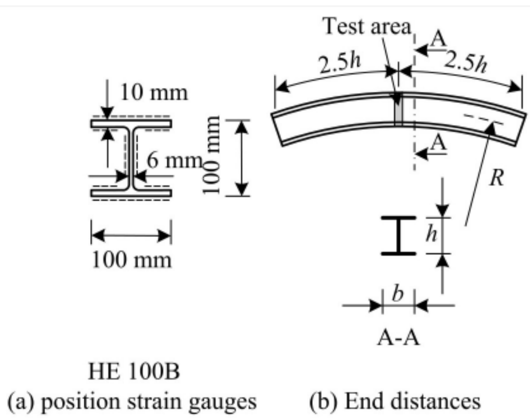

Figure 4 Location of strain gauges

4 RESULTS

4.1 Straight sections

The measured residual stresses of the straight reference sections are presented. The number of the specimen is related to its roller bent counterparts (Figure 5). It can be seen that the stresses are usually small and below 100 N/mm^2. Similar observations for straight hot-rolled HE 100B sections were made in [16].

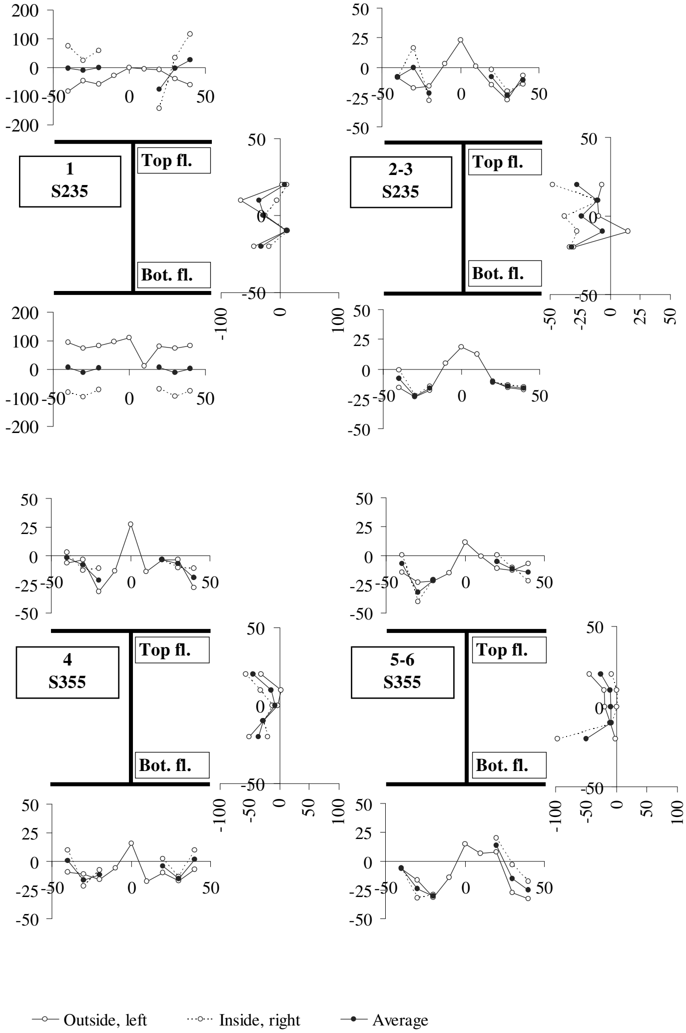

Figure 5 Hot rolled residual stresses in straight HE 100B reference sections in N/mm^2

4.2 Roller bent sections

A plot of the residual stresses of the roller bent specimens is shown in Figure 6. The top flange and bottom flange are referred to as the elongated flange and compressed flange, respectively. The theoretically obtained stresses for cold-bent sections as proposed by Timoshenko are shown alongside the measured stresses by using the measured yield stress (Table 2) of the straight reference sections and the shape factor on the basis of nominal section dimensions (Figure 1).

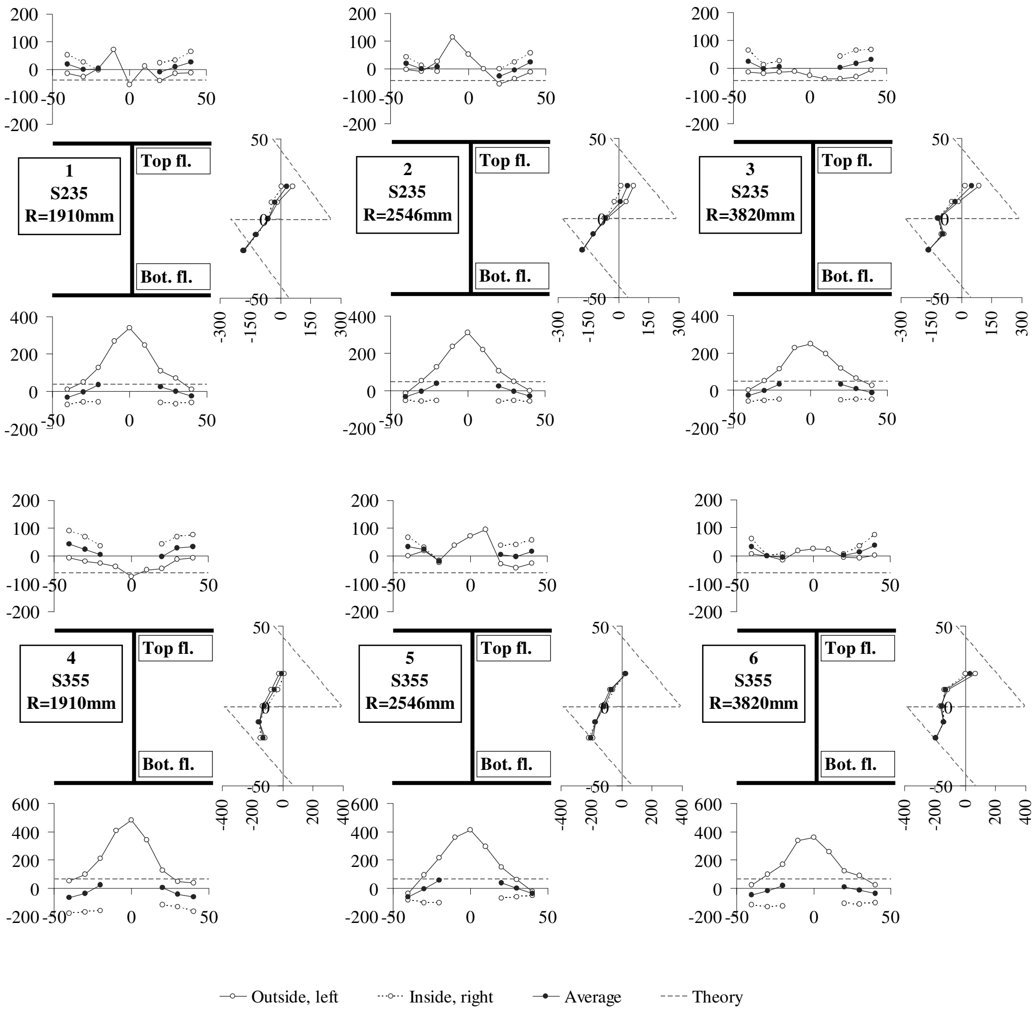

Figure 6 Residual stress distributions after roller bending of HE 100B sections in N/mm^2.

5 DISCUSSION

The residual stresses as shown in Figure 6 display the following characteristics. High tensile residual stresses were observed at the web-to-flange junction in the bottom flange. The web of the roller bent specimens is primarily under compression. Small residual stresses, either in compression or tension, were found in the top flange. The results show a symmetrical stress pattern with respect to the minor axis of bending.

The net effect of the roller bending process on the residual stresses can be observed by comparing Figure 5 with Figure 6. It can be seen that the roller bending process results in a residual stress pattern that is entirely different from the hot-rolled pattern prior to bending. In particular, the maximum residual stress of the roller bent sections is much larger compared to the maximum residual stress of the straight hot-rolled sections.

Bending a beam into a smaller radius requires an increase in cold work and hence an expected increase in residual stress. However, it can be observed that the bending radius has small influence on the residual stress distribution.

The effect of the steel grade on the residual stress distributions in roller bent sections for the HE 100B series can be observed by comparing the results of specimens 1 to 3 (Figure 6) with those of specimens 4 to 6. The effect of the steel grade is significant since the residual stresses of the specimens 1 to 3 (S235) are much smaller than those of specimens 4 to 6 (S355).

The measured residual stresses of the roller bent specimens are generally below the yield stress of the straight material, although the yield stress was exceeded by the residual stress values in the bottom flange. A higher residual stress than the yield stress can be expected as a result of cold working the material during the roller bending process. The additional tensile tests on coupons taken from curved sections support this theory as they showed an increased yield stress (Figure 3). Recent findings as reported in [17] have shown a similar phenomenon for residual stresses in stainless steel sections.

The experimental results are quite different from the theoretically obtained residual stresses in cold-bent sections as proposed in [12]. The theoretical residual stress distribution does not have a stress gradient along the flange width, which was clearly observed in all experimental results. An antisymmetric stress pattern with respect to the major axis of bending postulated by theory has not been measured.

6 CONCLUSIONS

This paper presents experimental results of residual stress measurements carried out on straight and roller bent HE 100B sections. The results are part of a larger experimental and numerical study on residual stresses due to roller bending of wide flange steel sections. The sectioning method in conjunction with electrical strain gauges was employed to measure the residual stresses. The experimental results for the roller bent specimens showed a significantly different residual stress distribution when compared to the residual stress distributions in their straight counterparts. In the roller bent specimen, high compressive and high tensile stresses were observed in the web and in the bottom flange respectively. The observations clearly indicate that a hot rolled residual stress pattern is not applicable to a roller bent specimen. Also it can be stated that the theoretical solution for residual stresses in cold-bent members as proposed by Timoshenko is not suitable for roller bent wide flange steel sections. The large deviations between the theory and the experiments show that the roller bending process of wide flange steel sections cannot be simplified by a beam subjected to loading and unloading in uniform bending.

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