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Proposed residual stress model for hot-rolled wide flange steel cross sections

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Abstract

Residual stresses in hot-rolled wide flange steel cross sections may lead to premature yielding, accelerated corrosion and brittle fracture of steel members. The above phenomena lead to a loss of a steel member's stiffness and resistance under mechanical loading. Available residual stress models are mostly based on residual stress measurements that date back to 1950s. Some of the drawbacks of these models relate to the lack of consistency in the considered parameters that affect the residual stress development within a steel cross section. Motivated by this, this paper proposes a new residual stress model for hot-rolled wide flange steel cross sections. The proposed residual stress model relies on a dataset of 80 experiments that are complemented by additional measurements done as part of the present study. A parabolic residual stress distribution, which is deduced from a constraint optimization problem, is fitted to the assembled data. The proposed residual stress distributions are generalized with the aid of rigorous statistical analyses. The results suggest that the residual stress model is highly dependent on the cross-sectional area and the depth-to-width ratio of a hot-rolled wide flange steel cross section. The proposed residual stress model reduces the error, on average, by 60-70% compared to available residual stress models (e.g., European Convention for Constructional Steelwork model), regardless of the cross-sectional geometry of the hot-rolled cross section.

Keywords

Residual stresses, Residual stress measurements, Hot-rolled steel profiles, Wide flange shapes, Statistical analyses, Sectioning method

1 Introduction

Residual stresses are formed during the manufacturing process of a steel member. These processes could be: (a) cold forming, (b) uneven cooling, and/or (c) welding [1]. During the cold forming process, residual stresses are attributed to inelastic strain deformations that are unevenly developed [2]. In the latter two cases, residual stresses are formed due to differential cooling rates within the steel plates after the rolling process and/or welding.

Residual stresses develop due to uneven cooling in the web and the flange plates of a hot-rolled wide flange steel cross section, which is the primary focus of the present work. Referring to Figure 1, proceding the rolling process, the flange plate edges and the web central region cool down faster compared to the flange-to-web joint that is surrounded by a bigger portion of steel material. The early cooling regions develop an increased Young's modulus at an earlier stage compared to the late cooling regions. Therefore, the former regions restrain the contraction of the latter ones during the cooling process. As a result, the

flange-to-web joint develops tensile residual stresses, while the flange plate edges and the web central region develop compressive stresses to satisfy equilibrium within the cross section. Parabolic distributions (see Figure 1) are found to describe best the distributions in the web and flange plates [3], [4].
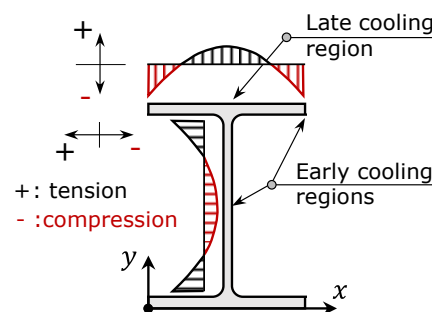

Figure 1 Residual stress distributions in hot-rolled wide flange steel cross sections

Out of the parameters that affect residual stresses in hot-

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rolled wide flange steel cross sections, the geometry of the section, the rolling and cooling process and potential cold straightening, prevail [1], [5]–[7]. Cold straightening is applied in structural steel members when they do not comply with the geometric tolerances of design specifications [8]–[10]. This process entails redistribution of residual stresses within a steel member and results in asymetrical residual stress distributions [11], [12]. The yield strength of the steel material is found not to affect the magnitude of residual stresses [1], [3], [5]–[7], [13].

Residual stresses may lead to premature yielding, accelerate global geometric instabilities, corrosion and fatigue in structural steel members [14]. The influence of residual stresses in reducing the lateral load capacity of steel members was identified in 1950s at Lehigh University from experimental research on steel columns [6], [15]. Subsequent studies showed that the presence of residual stresses in hot-rolled wide flange sections reduce the flexural and lateral-torsional buckling resistance of steel members due to premature yielding and the increase of the Wagner coefficient [16]–[20]. Comparisons of experimental data with finite element models show that the difference in predicting the flexural member resistance may be underestimated by 30% when residual stresses are disregarded in the numerical simulations [21].

The magnitude of residual stresses is affected by a number of uncertain parameters. Consequently, estimating residual stresses in wide flange hot-rolled cross sections may be challenging [22], [23]. In prior work, residual stress models for non-straightened hot-rolled wide flange sections have been proposed [3], [4], [6], [24]–[26]. Szalai and Papp [4] and Bradford and Trahair [25] proposed models of similar nature. They relied on parameters such as the flange area, A_f, the web area, A_w, the height of the cross section, h, the flange thickness, t_f, and the flange width, b_f. In these models, residual stresses are assumed to be proportional to the material yield strength, f_y, while the Wagner coefficient is assumed to be zero. Galambos and Ketter [6] introduced a model that relies exclusively on f_y, contrary to the model by Young [3]. The Young model [3] was developed based on limited residual stress measurement data on wide flange sections with weight, W, between 19 kg/m and 280 kg/m. It was found that residual stresses strongly depend on A_w/A_f. The European Convention for Constructional Steelwork (ECCS) model [24] relies on f_y and indirectly on h/b_f.

The development of available residual stress models for hot-rolled wide flange cross sections is mostly based on experimental data that date back to 1950s-1970s. Therefore, the development of an improved residual stress model for hot rolled cross sections is timely.

Within such a context, this paper proposes a new residual stress model for hot-rolled wide flange steel cross sections. Initially, a database of 80 residual stress data is assembled and supplemented by five additional residual stress measurements conducted as part of the present study. Available residual stress models are, then, assessed based on the developed dataset. Finally, a new residual stress model is developed based on a formulated constraint least square optimization problem and rigorous statistical analyses.

2 Residual stress dataset for hot-rolled wide flange cross sections

Figure 2 shows available residual stress experimental data on 80 hot-rolled wide flange cross sections with respect to t_f and h/b_f [3], [5], [11], [13], [18], [20], [26]–[37]. Superimposed are available European cross sections. The assembled database comprises cross sections with t_f varying from 5.7 mm to 130 mm, and h/b_f ranging from 1 to 3. Various steel grades are considered from manufacturers in North America, Europe and the UK. Effectively, f_y ranges from 235 MPa to 460 MPa. The measurements in these sections were mostly conducted between the 1950s and the 1970s. Although the assembled data covers a wide range of the $h/b_f - t_f$ space, there is still need for additional measurements to develop a generalized residual stress model.
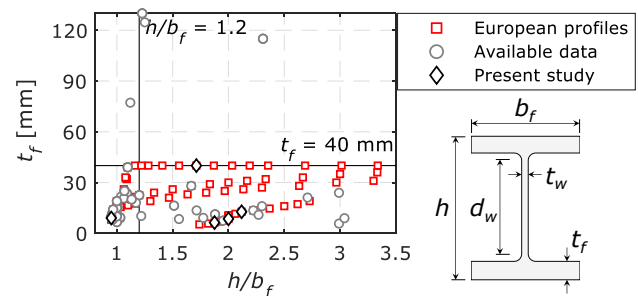

Figure 2 Available residual stress experimental data on hot-rolled wide flange steel cross sections with respect to t_f and h/b_f

3 Experimental program on hot-rolled wide flange cross section residual stresses

3.1 Overview of the experimental program

Five residual stress measurements were conducted to supplement the assembled dataset of hot-rolled wide flange cross section residual stresses. The steel members are made of S355-J2 with a nominal material yield strength of 355 MPa.

The purpose of the present experimental program was threefold; expanding the assembled database, and investigating the effect of the steel grade and the different fabrication techniques on residual stresses. To achieve the former goal, an IPE 120 and an HEM 500 were tested. With regards to the second goal, the IPE 200 and the IPE 360 of the present study were contrasted with the same profile measurements, but with $f_y = 235$ MPa [11], [31]. Finally, the HEA 160 European profile may be compared with the W6x20 equivalent US profile, which was tested by Dibley [20]. Due to brevity, this paper focuses on the former two objectives of the experimental program. The examined cross sections after completing the sectioning method [38] are illustrated in Figure 3. The geometric properties of the corresponding cross sections are summarized in Table 2.

The destructive sectioning method is employed for the residual stress measurements [38], [39]. This method provides reliable measurements and has been employed in prior research [3], [34]. In brief, it relies on the Hooke's law applied in measurements at each slice, before and after slicing. For this purpose, a conical head was utilized to produce slice markings at predefined gauge lengths of

110 mm and 250 mm that correspond to the gauge length of the extensometer. The presented results consider the measurements extracted from the 250 mm gauge length, since they are deemed more reliable. Corrections for potential slice curvature and temperature differences before and after slicing were also considered as described in previous work [40].
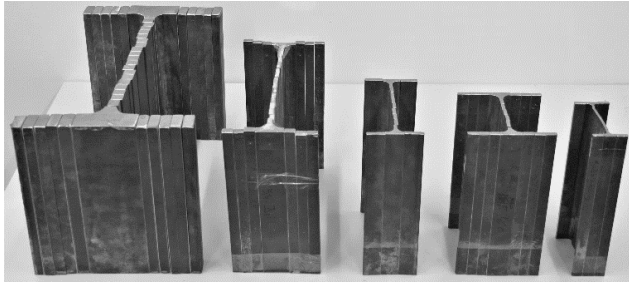

Figure 3 Side view of the sliced cross sections after sectioning (from left to right: HEM 500, IPE 360, IPE 200, HEA 160, and IPE 120)

Table 2 Geometric and material properties of the examined cross sections

Profile	A [mm²]	h/b_f	t_f [mm]	$b_f/2t_f$	d_w/t_w
IPE 120	1320	1.88	6.3	3.49	20.9
HEA 160	3880	0.95	9.0	6.89	17.3
IPE 200	2850	2.00	8.5	4.12	28.2
IPE 360	7270	2.12	12.7	4.96	37.3
HEM 500	34400	1.71	40.0	2.88	18.6

3.2 Experimental results

The measured residual stresses of the flanges and the web of the IPE 120 and the HEM 500 cross sections are depicted in Figure 4. The ECCS [24] and Young [3] models are superimposed in the same graph for comparison purposes. The results highlight that the assumed parabolic resisual stress distributions for the flanges and the web are reasonable. Moreover, in all cross sections, there was consistency in the measurements of both flanges. The residual stresses increase when the cross-sectional area, A, increases. This is consistent with prior work by Spoorenberg et al. [11]. Conversely, the ECCS model [24] solely relies on f_y and h/b_f. From Figure 4, the ECCS model does not depict correctly the residual stress distributions. Similar observations hold true for Young's model [3] that relies on A_w/A_f, but not on the total cross-sectional area.

A thorough comparison of all available residual stress models [3], [4], [6], [24]–[26] with the assembled test data suggests that the generality of these models in depicting accurately the residual stresses in hot-rolled wide flange steel cross sections is fairly limited.

3.3 Effect of yield stress on residual stresses

Figure 5 compares the residual stress measurements of the IPE 200 and the IPE 360 cross sections of the present study with prior measurements ([31] and [11]) of nominally identical sections featuring a lower f_y (i.e., $f_y = 235$ MPa). From this figure, cross sections with a lower f_y

may develop at least 50% higher residual stresses compared to their higher f_y counterparts. This is in line with prior research [1], [3], [5]–[7], [13] and contradits the majority of available residual stress models [4], [6], [24]–[26].
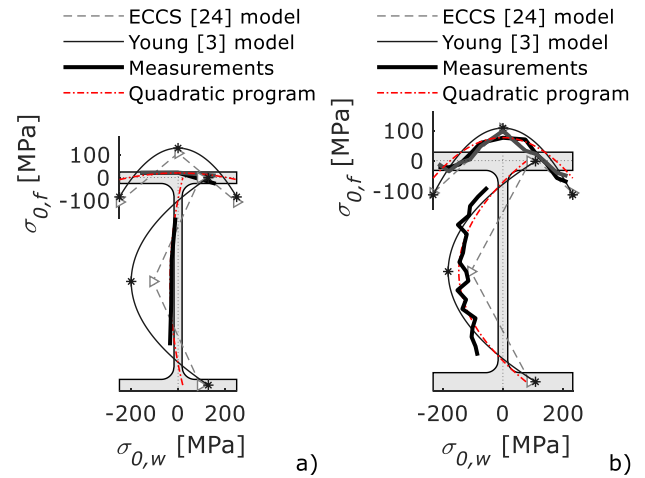

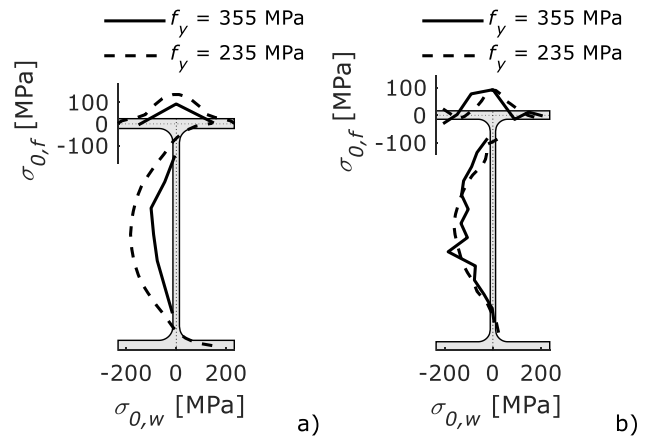**Figure 4** Residual stress measurement results of the present study: a) IPE 120, and b) HEM 500

Figure 5 Residual stress measurements in cross sections with variable yield stress: a) IPE 200 by the present study and [31], and b) IPE 360 by the present study and [11]

4 Proposed residual stress model for hot-rolled wide flange cross sections

4.1 Methodology

The development of the residual stress model relies on a constrained least square optimization method that is formulated as the quadratic program of Equation 1. The aim is to minimize the least squares of the residual stress observations with respect to the residual stress model (see Equation 1a) by respecting a set of equality constraints (see Equation 1b).

$$\text{minimise} \quad \frac{1}{2}\mathbf{x}^T\mathbf{P}\mathbf{x} + \mathbf{q}^T\mathbf{x} \tag{1a}$$

$$\text{subjected to} \quad \mathbf{A}\mathbf{x} = \mathbf{b} \tag{1b}$$

Where: vector $\mathbf{x}$ comprises the optimization variables, and matrix $\mathbf{P}$ and vector $\mathbf{q}$ describe the objective function.

The model assumes parabolic residual stress distributions

for both flanges and the web, as described in Equations 2a and 2b, respectively [3], [4]. The coordinate system of Figure 1 is followed. The residual stress distributions in both flanges are identical due to symmetry.

$$\sigma_{0,f}(x) = a + b \cdot \left(x - b_f/2\right)^2 \qquad (2a)$$
$$\sigma_{0,w}(y) = c + d \cdot (y - h/2)^2 \qquad (2b)$$

The quadratic program is subjected to two constraints (see Equations 3a and 3b); force equalibrium within the cross section, and continuity of residual stresses in the flange-to-web joint. Given the four coefficients of the residual stress distributions of Equation 2 and the two Equations (3a and 3b) that relate those, the proposed residual stress model is based on coefficients a and c. These coefficients describe the maximum tensile and compressive stresses in the flanges and the web, respectively.

$$\left(2t_f b_f\right)a + \left(\frac{2t_f b_f^3}{12}\right)b + \left[t_w(h - 2t_f)\right]c + \left[\frac{t_w\left(h - 2t_f\right)^3}{12}\right]d \qquad (3a)$$
$$a = c + d \cdot \left(h - t_f\right)^2/4 \qquad (3b)$$

Figure 4 shows characteristic examples of the quadratic program results. The proposed methodology provides an accurate representation of the residual stresses in the web and the flanges of cross sections, regardless of their geometry. Therefore, the proposed residual stress model may rely on the formulated optimization method.

4.2 Observations and statistical analysis

Prior work has highlighted the influence of cross-sectional geometric parameters on residual stresses. While there is no consensus between those, the following prevail: $A_f, A_w, h, t_f, b_f, h/b_f, A, A_w/A_f$. Figure 6 shows relations between the coefficient a (see Equation 2a) and the geometric parameters A and h/b_f. The data is distinguished in steel fabricated before 1992 and after 2010 that describe the entire dataset. This differentiation acknowledges potential impact of different manufacturing processes over time on residual stresses.
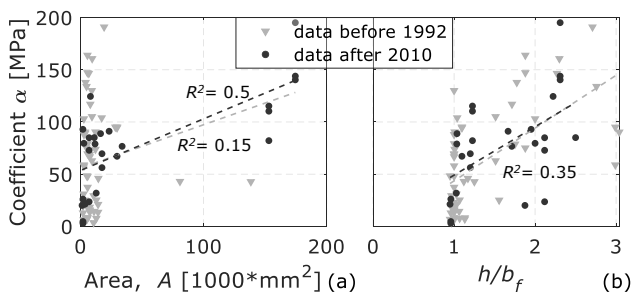

Figure 6 Coefficients of the optimization method with respect to: a) A, and b) h/b_f

From Figure 6a, qualitatively, when A increases, the peak tensile residual stress in the flange-to-web joint increases. This may be attributable to the decrease of cooling rate once A increases [11]. From Figure 6b, same observations hold true when h/b_f increases. The h/b_f is collinear with A_w/A_f; while this observation is consistent with Young [3], it contradits the ECCS residual stress model [24]. The coefficient of determination, R^2, in the highlighted relations ranges from 0.2 to 0.4. Depending on the

coefficient, an increase by almost two times in the R^2 is observed for cross sections manufactured after 2010.

Vis-à-vis the above discussion, multiple linear regression analysis is performed for the development of the residual stress model [21]. The full dataset is utilized for this purpose. Stepwise regression analysis is conducted [41], by considering the most influential predictor variables, $X = [h, A, h/b_f, A_w/A, d_w/t_w, t_f]$, as shown in Equation 4. The predictor variables are bounded within [-1, 1] after being normalized according to Equation 5.

$$y = \beta_0 + \beta_1 \cdot \bar{h} + \beta_2 \cdot \overline{A} + \beta_3 \cdot \overline{h/b_f} + \beta_4 \cdot \overline{A_w/A} + \beta_5 \cdot \overline{d_w/t_w}$$
$$+ \beta_6 \cdot \overline{t_f} + \varepsilon \qquad (4)$$

$$\overline{X}_i = 2 \cdot \frac{X_i - \min(X_i)}{\max(X_i) - \min(X_i)} \qquad (5)$$

Where: y is the response variable (i.e., a or c), β_i are the coefficients of the regression, ε is the residual of the regression model, and $\min(X_i)$ and $\max(X_i)$ are the minimum and maximum values of X_i.

The regression analysis excludes variables with increased collinearity. Moreover, the quality of the analysis is ensured by respecting: (a) normality of residuals, (b) homogeneity of variances, and (c) no correlation between the residuals and the predictor variables, as per the Gauss-Markov theory [41].

4.3 Residual stress model

The proposed residual stress model coefficients a and c are shown in Equation 6. Statistical F-tests on the significance of the proposed equations resulted in p-values lower than $1e^{-6}$, thereby indicating the robustness of the proposed model. The predictor variables range as follows: $1320\,\text{mm}^2 \leq A \leq 175000\,\text{mm}^2$ and $0.95 \leq h/b_f \leq 3.0$. These bounds are considered in Equation 5 to de-normalize the corresponding variables. Statistical analysis considering residual stresses normalized with respect to f_y were not statistically significant compared to the proposed model, which is consistent with Young's model [3]. Conversely, the ECCS suggests the opposite [24].

$$a = 107 + 51 \cdot \overline{h/b_f} + 20 \cdot \bar{A} \quad , \sigma_a = 37\,\text{MPa} \qquad (6a)$$
$$c = -\left(142 + 84 \cdot \overline{h/b_f}\right) \quad , \sigma_c = 81\,\text{MPa} \qquad (6b)$$

To evaluate the robustness of the proposed residual stress model, the 1-norm of the difference between the residual stress measurements and available model predictions is computed. The 1-norms for the flanges and the web are normalized to the maximum norm, based on all considered models [3], [4], [6], [24]–[26].

Figure 7 depicts the normalized 1-norms for the flanges of all the collected test data sorted in ascending order of h/b_f. The mean of the calculated 1-norms is 30% higher in the proposed model compared to the quadratic program that provides an optimal fit to the data. The source of error in the quadratic program is attributed to the distribution of the measured residual stresses that may not always follow a perfect quadratic equation. Contrary to the proposed model, the error of the ECCS model is nearly two times higher than that from the quadratic program [24]. Similar

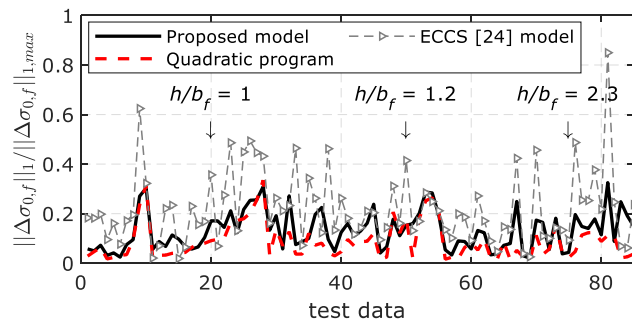observations hold true for the residual stresses in the web.

Figure 7 Normalised 1-norms of the difference between residual stress measurements in the flange of a hot-rolled wide flange cross section and the proposed model, the ECCS [24] model and the quadratic program

To quantify the errors in predicting residual stresses between the proposed and the ECCS [24] models, Figure 8 shows the histograms of the 1-norms for both cases. The histograms are fitted with log-normal distributions. Their probability density functions are also superimposed in the same figures. The resultant mean of the log-normal distribution of the proposed model is nearly 50% less than that of the ECCS model [24]. Interestingly, the variance of the proposed model is four times smaller than that of the ECCS model.
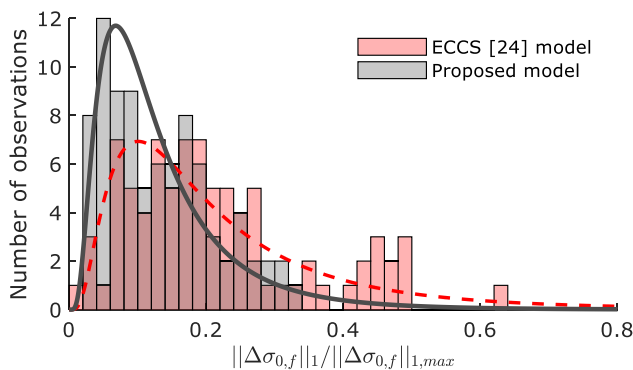

Figure 8 Histograms of the normalised 1-norms of the difference between residual stress measurements in the flange of a hot-rolled wide flange cross section and the proposed model and the ECCS [24] model

5 Conclusions

This paper introduces a new residual stress model for hot-rolled wide flange non-straightened steel members. A dataset of residual stress measurements on such sections is, first, assembled. This comprises 80 data from prior studies and five complementary measurements conducted by the authors. A least square optimization problem in the form of a quadratic program is formulated and is found to explain accurately the residual stress measurements. Therefore, the model is based on the formulated quadratic program and rigorous statistical procedures. The primary findings of this study are summarised as follows:

Contrary to available residual stress models in the literature (e.g., the ECCS model [24]), the impact of material yield stress, f_y, on the magnitude and shape of residual stresses in hot-rolled wide flange cross sections is not substantiated. Comparisons of available data, as well as statistical analysis highlighted no correlation between f_y and the magnitude of residual stresses.

The ECCS model [24] does not predict accurately residual stresses in hot-rolled wide flange steel sections. The primary reason is the dependence of this model on f_y rather than pertinent geometric properties of the cross section.

The peak tensile residual stresses in the flange of a hot-rolled wide flange steel section are best described by the cross-sectional area, A, and the cross-sectional height-to-flange width ratio, h/b_f. The latter strongly influences the peak compressive residual stresses in the web.

The proposed model predicts with a similar accuracy the residual stress distributions with optimally fitted data (i.e., quadratic program). On the other hand, the resultant error of available models in the literature is at least two times higher than that of the proposed model.

Acknowledgements

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