EXPERIMENTAL EVALUATION AND MODELING OF RESIDUAL STRESS DISTRIBUTIONS FOR HOT-ROLLED WIDE FLANGE STEEL MEMBERS

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1. ABSTRACT

Local and member instability modes in structural steel members are influenced by initial geometric imperfections and residual stresses among other parameters. The robustness of stability-related design provisions and finite element modeling procedures of steel members relies on the accuracy of the accounted residual stresses. Numerous residual stress models exist in literature. However, they are based on experimental work that dates to early 1950s. In this paper, the validity of available residual stress models is assessed based on a dataset of physical residual stress measurements of more than 80 wide flange cross sections. This dataset was complemented with measurements on five additional wide flange cross sections. Collectively, it is found that the accuracy of available residual stress models, such as the commonly used ECCS model, is not sufficient in most cases. For this reason, we propose a residual stress model that was derived based on a constrained optimization problem between the experimental observations and an assumed quadratic residual stress distribution. The mean error between the proposed model and all observations reduces by 70% compared to available models in the literature. Moreover, the corresponding variance reduces by up to four times.

2. INTRODUCTION

Residual stresses form during the manufacturing process of structural steel members. In hot-rolled wide flange members, which constitute the primary focus of this paper, residual stresses are formed after the rolling process due to uneven differential cooling within the web and flange plates [1]. Referring to Fig. 1a, the more exposed regions of web centre and flange edge tend to cool down faster than the late cooling region of the flange-to-web intersection. Therefore, the early cooling regions develop an increased Young's modulus compared to the late cooling ones. This results in tensile stresses in the latter region that is restrained from contraction by the former one. To satisfy equilibrium within the cross section, the web centre and the flange edges are subjected to compression. The distribution that best describes the evolution of residual stresses within the section is parabolic [2].

The presence of residual stresses in structural steel members may lead to premature yielding and instabilities and it may accelerate corrossion and fatigue [3]. The effect of residual stresses in reducing the axial and the lateral load resistance of steel members was first identified in 1950s at Lehigh University from experiements of steel columns [4], [5] and was later extensively validated [6]–[8]. These studies showed that residual stresses strongly affect the buckling resistance of steel members subjected to increased axial loads and intermediate normalised slenderness [9]. This is highlighted in Fig. 1b that illustrates the axial or moment capacity reduction factor of a membrer with respect to its normalised slenderness with and without residual stresses.

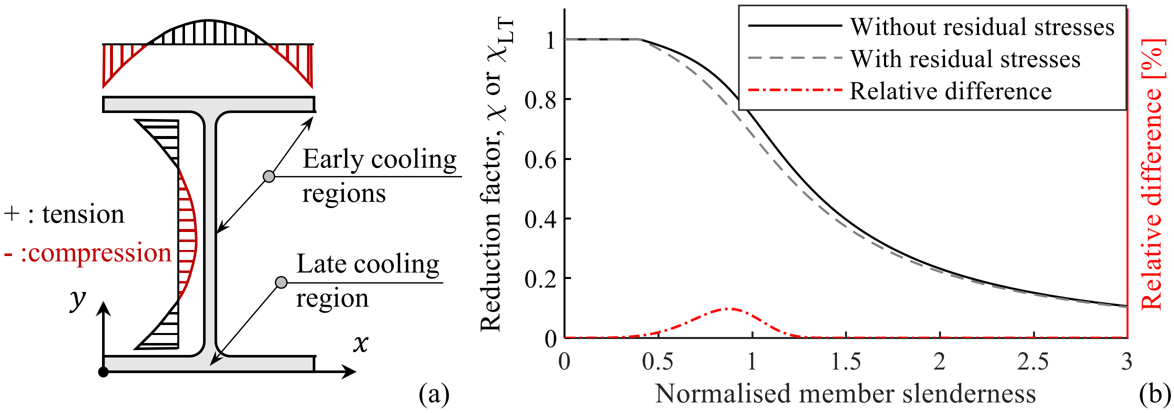

Fig. 1 (a) Formation of residual stresses in hot-rolled wide flange sections, and (b) member strength reduction factor versus normalised member slenderness with and without residual stresses

The parameters that mostly influence the formation of residual stresses in hot-rolled wide flange steel members are the cross-sectional geometry, the rolling and cooling process and the potential cold-straightening [4], [10], [11]. However, there is no consensus in literature regarding the effect of the material yield stress on the residual stresses [2], [4], [11]. Regardless of the increased uncertainty in predicting residual stresses in hot-rolled wide flange steel members [12], residual stress models exist in literature. For instance, Szalai and Papp [13] and Bradford and Trahair [14] relied on the (a) flange area, A_f, (b) the web area, A_w, (c) the height, h, (d) the flange thickness, t_f, (e) the flange width, b_f, and (f) the material yield stress, f_y, in their proposed models. Contrary to Young's model [2], Galambos and Ketter [4] and the European Convention for Constructional Steelwork (ECCS) [15] developed a model that relies on f_y. The Young's model [2] acknowledged the strong dependence of the magnitude of residual stresses with A_w/A_f. However, this model was calibrated to limited measurements on wide flange sections with weight, W, between 19 kg/m and 280 kg/m. It is understood that the development of a new model to predict residual stresses in hot-rolled wide flange steel members is timely.

To this end, this paper proposes a new residual stress model for non-straightened hot-rolled wide flange steel members. The model development is informed by a residual stress measurement dataset that was supplemented with five additional measurements conducted as part of this study. The developed model relies on thorough statistical analysis and a formulated constraint optimisation problem.

3. EXPERIMENTAL DATA AND ADDITIONAL MEASUREMENTS ON RESIDUAL STRESSES OF HOT-ROLLED WIDE FLANGE MEMBERS

A residual stress dataset is developed comprising nearly 80 measurements based on research conducted on steel grades fabricated in the US, the UK, Canada, Europe between 1958 and 2021 [2], [7], [8], [10], [16]–[29]. According to Fig. 2, the web and flange local slenderness of available data range from 3 to 54 and from 1.3 to 9.4, respectively. Moreover, the flange thickness ranges from 5.7 mm to 130 mm and the cross-sectional aspect ratio, h/b_f, ranges between 1.0 and 3.0. Most of the cross sections are classified as Class 1 and 2 according to CEN [30].

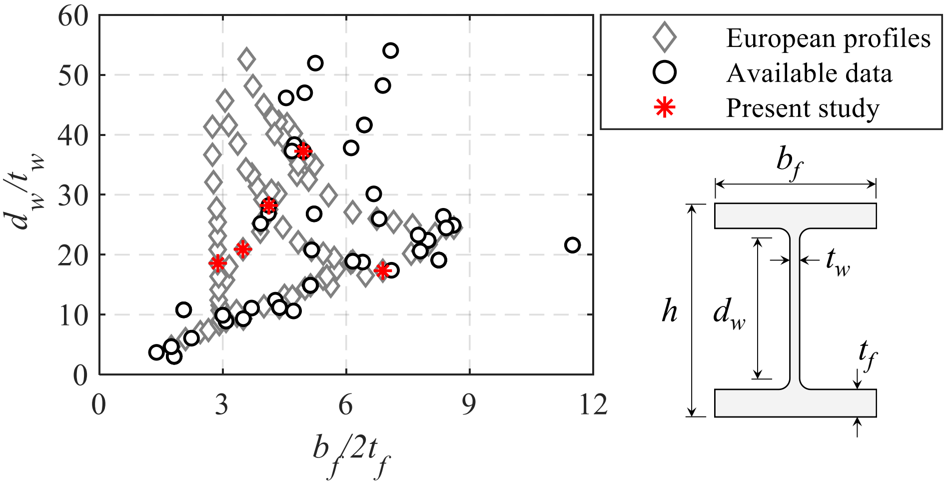

Fig. 2 Available residual stress data with respect to d_w/t_w *and* $b_f/2t_f$

To supplement the assembled dataset, five additional measurements are conducted in an IPE 120, HEA 160, IPE 200, IPE 360, and HEM 500 European profiles made of S355-J2 (i.e., f_y = 355 MPa). Basic geometric and material characteristics of the steel sections under examination are shown in Table 1. These profiles are selected (a) to expand the assembled dataset in terms of cross-sectional geometric characteristics (IPE 120 and HEM 500), (b) to investigate the effect of regional differences on residual stresses (HEA 160 compared to the equivalent W6x20 US profile by [8]), and (c) to investigate the effect of steel grade on residual stresses (IPE 200 and IPE 360 compared to measurements on nominally identical profiles and lower yield stress by [16], [23]). While the former aspect is discussed in this paper due to brevity, details on the remaining ones are found in Skiadopoulos et al. [31], [32].

Profile	A [mm^2]	h/b_f	t_f [mm]	$b_f/2t_f$	d_w/t_w	f_y [MPa]
IPE 120	1320	1.88	6.3	3.49	20.9	355
HEA 160	3880	0.95	9.0	6.89	17.3	355
IPE 200	2850	2.00	8.5	4.12	28.2	355
IPE 360	7270	2.12	12.7	4.96	37.3	355
HEM 500	34400	1.71	40.0	2.88	18.6	355

Table 1 Characteristic geometric and material properties of the examined steel members

The measurements are conducted according to the sectioning method [33], which has been extensively used in the literature. In brief, this method relies on the uniaxial relaxation of stresses after slicing the steel member. To achieve this, indentations were marked at each member slice before slicing at a predefined gauge length of 250 mm. The normalized difference of the distance between markings before and after slicing equals the uniaxial residual strains which are, then, translated to residual stresses, according to the Hooke's law. Fig. 3 depicts the selected cross sections together with their markings, after slicing.

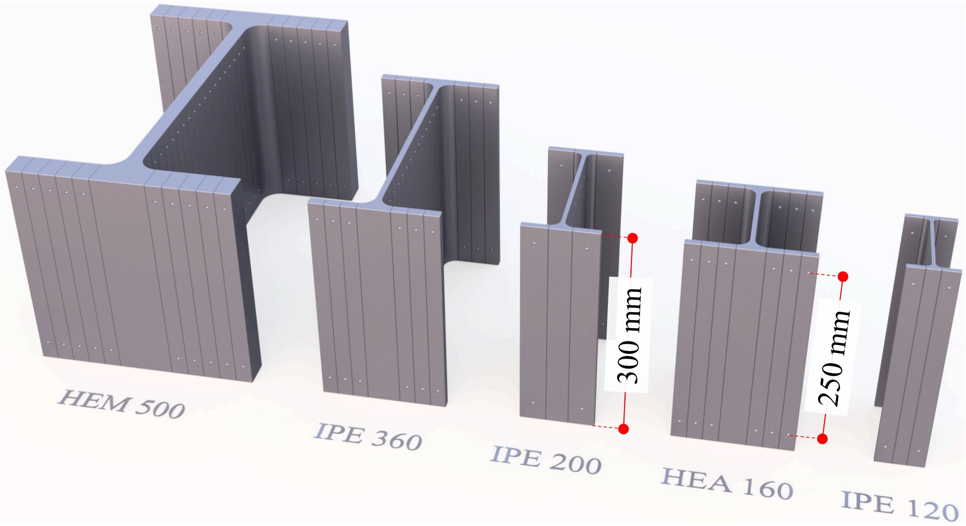

Fig. 3 Schematic of the sliced cross sections (in scale)

The residual stress measurements for the IPE 120 and the HEM 500 are highlighted in Fig. 4a and 4b, respectively. It is demonstrated that for the lightest cross section, the ECCS [15] and Young [2] models are not at all accurate. Lighter sections tend to develop lower residual stresses [16]. Contrary to that, the ECCS model [15] considers only the material yield stress as the primary factor affecting residual stresses. Similar observations hold for the Young's model [2] that solely relies on A_w/A_f. The distributions in the web and the flange follow reasonably well the parabolic distribution shape assumed by Young [2]. Both flanges develop almost matching residual stresses, due to symmetry in the cross section. A thorough review of all available residual stress models highlights that none of them enjoys generality in depicting residual stresses in hot-rolled wide flange members.

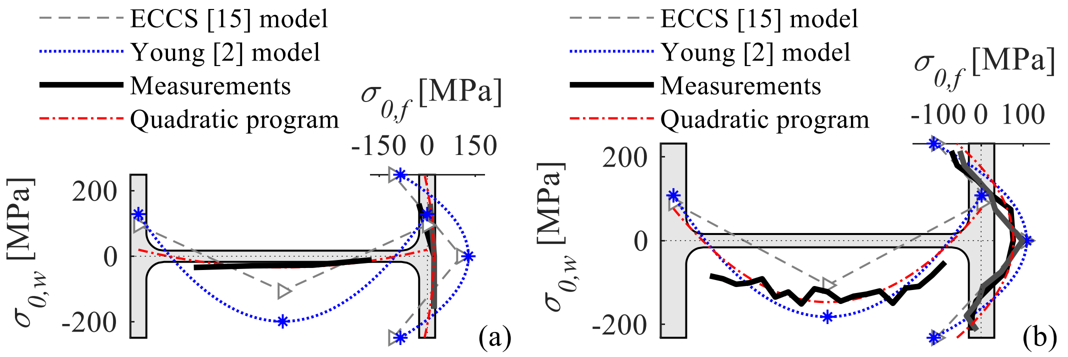

Fig. 4 Residual stress measurements and model predictions for the: (a) IPE 120 and the (b) HEM 500

4. RESIDUAL STRESS MODEL FOR NON-STRAIGHTENED HOT-ROLLED WIDE FLANGE STEEL MEMBERS

A constraint optimisation method is formulated based on the quadratic program expressed in Eq. (1). The optimisation method minimises the least squares of all available residual stress measurements [see Eq. (1a)], assuming a parabolic residual stress distribution for the web and the flanges, by respecting a set of constraints [see Eq. (1b)]. The residual stress distributions are depicted in Eqs. (2a) and (2b) for the flanges and the web, respectively, and they consider identical distributions in both flanges (coordinate system as per Fig. 1a).

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

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

Where: vector **x** comprises the optimization variables, and matrix **P** and vector **q** describe the objective function.

$$\sigma_{0,f}(x) = a + b \cdot \left(x - b_f/2\right)^2 \tag{2a}$$

$$\sigma_{0,w}(y) = c + d \cdot (y - h/2)^2 \tag{2b}$$

The constraints of the optimisation program are shown in Eqs. (3a) and (3b). The former assumes force equilibrium within the cross section, while the latter assumes continuity of residual stresses in the flange-to-web intersection. Having the two constraint equations and the four variables of the residual stresses, the proposed model provides a set of equations for coefficients a and c of Eq. (2). These describe the maximum tensile and compressive residual stresses in the flange and web centres, respectively. The proposed methodology is accurate in representing the residual stress distributions, as characteristically shown in Fig. 4. Therefore, the proposed model will rely on the formulated methodology.

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

$$a = c + d \cdot \left(h - t_f\right)^2/4 \tag{3b}$$

The development of the residual stress model relies on multiple linear regression between the response variables a and c [Eq. (2)] and predictor variables. Based on prior research work, the considered predictor variables are $X = [h, A, h/b_f, A_w/A, d_w/t_w, t_f]$. Fig. 5 shows characteristic trends of the response variable a with respect to A, h/b_f, and A_w/A_f and their corresponding coefficients of determination. To include potential differences in manufacturing processes, a distinction in the fabrication year in *before 1992* and *after 2010* is made. Fig. 5a highlights increasing residual stresses in the flanges with respect to increasing cross-sectional area, which is attributable to the higher rate of differential cooling once A increases. The cross-sectional area is statistically the most significant variable (Fig. 5a). Between h/b_f (Fig. 5b) and A_w/A_f(Fig. 5c), which are collinear, the former appears statistically more significant. Therefore, the former is selected for the residual stress model compared to the latter, which is employed in the Young model [2]. The above observations contradict the assumptions of the ECCS model [15].

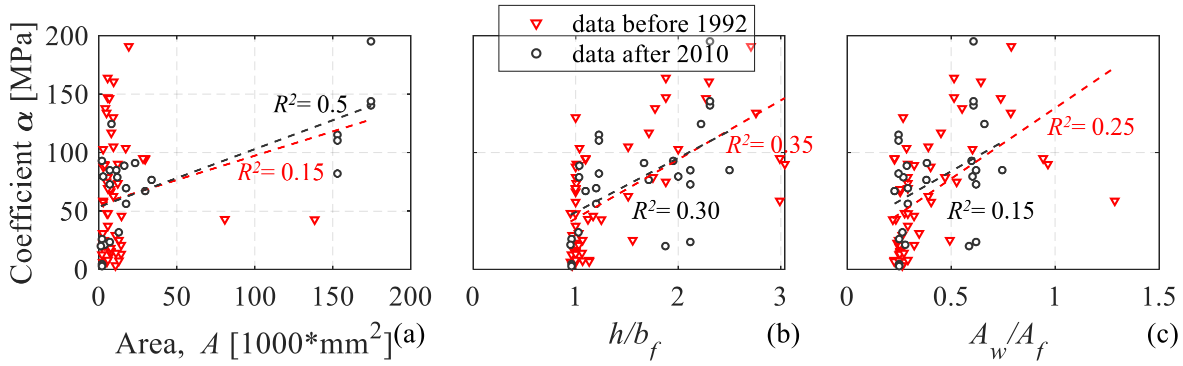

Fig. 5 Coefficient a of the quadratic program versus: (a) cross-sectional area, A, (b) h/b_f, and (c) A_w/A_f

Stepwise multiple linear regression analysis is conducted [34], as shown in Eq. 4a based on a normalisation of the predictor variables to bound them within [-1, 1] for comparability purposes. The robustness of the conducted analysis relies on: (a) exclusion of collinear variables, (b) normality of residuals, (c) homogeneity of variances, and (d) no correlation between predictor variables and regression residuals, according to Gauss-Markov [34].

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

$$\overline{X_i} = 2 \cdot \frac{X_i - \min{(X_i)}}{\max(X_i) - \min{(X_i)}} \tag{4b}$$

Where: y is the response variable, β_i are the regression coefficients, ε is the regression residual, and min (X_i) and max (X_i) are the minimum and maximum values of X_i.

The proposed model coefficients a and c are given in Eq. 5. The ranges of the predictor variables, which serve for de-normalization as per Eq. 4b, are $1320\,\text{mm}^2 \leq A \leq 175000\,\text{mm}^2$ and $0.95 \leq h/b_f \leq 3.0$. Contrary to the ECCS model [15], statistical analysis including f_y showed no statistical significance, contrary to the proposed equations that resulted in statistical p-values lower than $1e^{-6}$.

$$a = 107 + 51 \cdot \overline{h/b_f} + 20 \cdot \bar{A} \quad , \sigma_a = 37\ \text{MPa} \tag{5a}$$

$$c = -\left(142 + 84 \cdot \overline{h/b_f}\right) \quad , \sigma_c = 81\ \text{MPa} \tag{5b}$$

The accuracy of the proposed residual stress model is assessed through the compuration of the L1-norm of the difference between the residual stress measurements and the model predictions. The L1-norms are normalized to the maximum norm, based on all available models [2], [4], [13]–[15], [18]. Fig. 6 shows the histograms and their fitted log-normal distributions of the L1-norms for the proposed and the ECCS model [15]. It is demonstrated that the mean of the log-normal distribution of the proposed model is 50% less than that of the ECCS model [15], while the variance of the proposed model is four times smaller than that of the ECCS model.

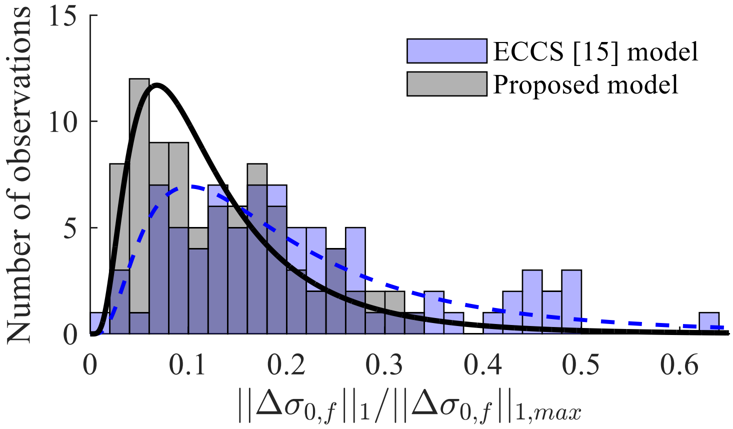

Fig. 6 Histogram of normalised L1-norm of the difference between flange residual stresses measurement data and model predictions

5. SUMMARY AND CONCLUSIONS

This paper proposes a residual stress model for hot-rolled wide flange steel members. First, a dataset of nearly 80 residual stress measurements is assembled and complemented with five additional measurements by the authors. The model development is based on statistical analysis and a least square optimization problem that is formulated and provides an accurate representation of the residual stress measurements. In brief, contrary to the ECCS model [15], the material yield stress, f_y, is not considered in the proposed model, because rigorous statistical analysis highlighted no correlation between f_y and the magnitude of residual stresses. This leads to a 50% lower error in predicting residual stresses utilising the proposed model, compared to the ECCS one [15]. The peak residual stresses in the center of the flange of a hot-rolled wide flange steel section are best described by the cross-sectional area, A, and the height-to-width ratio, h/b_f. The latter strongly influences the peak compressive residual stresses in the web.

6. REFERENCES

[1] BEEDLE, L.S. and TALL, L. 'Basic column strength', *Journal of the Structural Division*, Vol. 86, No. 7, 1960, pp. 139–173.

[2] YOUNG, B.W. 'Residual stresses in hot rolled members', *IABSE reports of the working commissions*, Vol. 23, No. 1, 1975, pp. 25–38, https://doi.org/10.5169/SEALS-19798.

[3] ABAMBRES, M. and QUACH, W.-M. 'Residual stresses in steel members: a review of available analytical expressions', *International Journal of Structural Integrity*, Vol. 7, No. 1, 2016, pp. 70–94, https://doi.org/10.1108/IJSI-12-2014-0070.

[4] GALAMBOS, T.V. and KETTER, R.L. 'Columns under combined bending and thrust', *Journal of the Engineering Mechanics Division*, Vol. 85, No. 2, 1959, pp. 1–30, https://doi.org/10.1061/JMCEA3.0000084.

[5] BEEDLE, L.S. 'The influence of residual stress on column strength - A proposed pilot investigation', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 220A.3.

[6] SHAYAN, S., RASMUSSEN, K.J.R. and ZHANG, H. 'Probabilistic modelling of residual stress in advanced analysis of steel structures', *Journal of Constructional Steel Research*, Vol. 101, 2014, pp. 407–414, https://doi.org/10.1016/j.jcsr.2014.05.028.

[7] LAMARCHE, C.-P. and TREMBLAY, R. 'Seismically induced cyclic buckling of steel columns including residual-stress and strain-rate effects', *Journal of Constructional Steel Research*, Vol. 67, No. 9, 2011, pp. 1401–1410, https://doi.org/10.1016/j.jcsr.2010.10.008.

[8] DIBLEY, J.E. 'Lateral torsional buckling of I-sections in grade 55 steel', *Proceedings of the Institution of Civil Engineers*, Vol. 43, No. 4, 1969, pp. 599–627, https://doi.org/10.1680/iicep.1969.7315.

[9] LU, A.Y.-C. and MACRAE, G. 'Residual stress effects on the seismic performance of low-rise steel frames', in *Proceedings of the Ninth Pacific Conference on Earthquake Engineering: Building an Earthquake-Resilient Society*, New Zealand Society for Earthquake Engineering, Inc., Wellington, New Zealand, University of Auckland, Auckland, New Zealand, 2011, pp. 1–7.

[10] FEDER, D. and LEE, G.C. 'Residual stress and the strength of members of high strength steel', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 269.2.

[11] HUBER, A.W. 'Residual stresses in wide-flange beams and columns', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 220A.25.

[12] FUKUMOTO, Y., ITOH, Y. and KUBO, M. 'Strength variation of laterally unsupported beams', *J. Struct. Div.*, Vol. 106, No. 1, 1980, pp. 165–181, https://doi.org/10.1061/JSDEAG.0005334.

[13] SZALAI, J. and PAPP, F. 'A new residual stress distribution for hot-rolled I-shaped sections', *Journal of Constructional Steel Research*, Vol. 61, No. 6, 2005, pp. 845–861, https://doi.org/10.1016/j.jcsr.2004.12.004.

[14] BRADFORD, M.A. and TRAHAIR, N.S. 'Inelastic buckling of beam-columns with unequal end moments', *Journal of Constructional Steel Research*, Vol. 5, No. 3, 1985, pp. 195–212, https://doi.org/10.1016/0143-974X(85)90003-3.

[15] ECCS 'Manual on stability of steel structures. Part 2.2 Mechanical Properties and Residual Stresses', Bruxelles: European Convention for Constructional Steelwork (ECCS), 1976.

[16] SPOORENBERG, R.C., SNIJDER, H.H. and HOENDERKAMP, J.C.D. 'Experimental investigation of residual stresses in roller bent wide flange steel sections', *Journal of Constructional Steel Research*, Vol. 66, No. 6, 2010, pp. 737–747, https://doi.org/10.1016/j.jcsr.2010.01.017.

[17] ALPSTEN, G.A. 'Thermal residual stresses in hot-rolled steel members', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 337.3.

[18] SPOORENBERG, R.C., SNIJDER, H.H., CAJOT, L.-G. and MAY, M.S. 'Experimental investigation on residual stresses in heavy wide flange QST steel sections', *Journal of Constructional Steel Research*, Vol. 89, 2013, pp. 63–74, https://doi.org/10.1016/j.jcsr.2013.06.009.

[19] ADAMS, P.F., LAY, M.G. and GALAMBOS, T.V. 'Experiments on high strength steel members', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 297.8.

[20] ALBERT, C., ESSA, H.S. and KENNEDY, D.J.L. 'Distortional buckling of steel beams in cantilever-suspended span construction', *Can. J. Civ. Eng.*, Vol. 19, No. 5, 1992, pp. 767–780, https://doi.org/10.1139/l92-088.

[21] AUGER, K. 'Conception parasismique des contreventements concentriques en treillis à segments multiples combinés aux poteaux gravitaires', PhD Thesis, Département des génies Civil, Géologique et des Mines École Polytechnique de Montréal.

[22] BROZZETTI, J., ALPSTEN, G.A. and TALL, L. 'Residual stresses in a heavy rolled shape 14WF730', Lehigh University, Bethlehem, PA, USA: Fritz Laboratory, Report Nr. 337.10.

[23] DADDI, I. and MAZZOLANI, F.M. 'Determinazione sperimentale delle imperfezioni strutturali nei profilati di acciaio', *Costruzioni Metalliche*, Vol. 5, 1971, pp. 3–23.

[24] DE CASTRO E SOUSA, A. and LIGNOS, D.G. 'Residual stress measurements of European hot-rolled I-shaped steel profiles', Lausanne: Ecole Polytechnique Federale de Lausanne, Report Nr. 231302.

[25] DUX, P.F. and KITIPORNCHAI, S. 'Inelastic beam buckling experiments', *Journal of Constructional Steel Research*, Vol. 3, No. 1, 1983, pp. 3–9, https://doi.org/10.1016/0143-974X(83)90011-1.

[26] JEZ-GALA, C. 'Residual stresses in rolled I-sections', *Proceedings of the Institution of Civil Engineers*, Vol. 23, No. 3, 1962, pp. 361–378, https://doi.org/10.1680/iicep.1962.10874.

[27] KETTER, R.L. 'The influence of residual stress on the strength of structural members', *Welding Research Council Bulletin Series*, Vol. 44, No. 1, 1958, pp. 1–11.

[28] SONCK, D., IMPE, R.V. and UNIVERSITY, G. 'Study of residual stresses in I-section members and cellular members', in *Proceedings of the Annual Stability Conference Structural Stability Research Council St. Louis, Missouri*, Curran Associates, Inc., St. Louis, MO, USA, 2013, pp. 584–602.

[29] TANKOVA, T., RODRIGUES, F., LEITÃO, C., MARTINS, C. and SIMÕES DA SILVA, L. 'Lateral-torsional buckling of high strength steel beams: Experimental resistance', *Thin-Walled Structures*, Vol. 164, 2021, pp. 107913, https://doi.org/10.1016/j.tws.2021.107913.

[30] CEN 'EN 1993-1-1: Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings', Brussels, Belgium: European Committee for Standardization, 2005.

[31] SKIADOPOULOS, A., DE CASTRO E SOUSA, A. and LIGNOS, D.G. 'Experiments and proposed model for residual stresses in hot-rolled wide flange shapes', *Journal of Constructional Steel Research*, Vol. 210, 2023, pp. 108069, https://doi.org/10.1016/j.jcsr.2023.108069.

[32] SKIADOPOULOS, A., SOUSA, A. de C. e and LIGNOS, D.G. 'Proposed residual stress model for hot-rolled wide flange steel cross sections', in *Proceedings 10th European Conference on Steel and Composite Structures*, Ernst & Sohn, Amsterdam, Netherlands, 2023.

[33] LUXION, W.W. and JOHNSTON, B.G. 'Plastic behavior of wide-flange beams', *Welding Journal*, Vol. 27, No. 11, 1948, pp. 538–554.

[34] CHATTERJEE, S. and HADI, A.S. 'Regression analysis by example', Hoboken, NJ: Wiley, 2015.

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1. ΠΕΡΙΛΗΨΗ

Η ευστάθεια μελών μεταλλικών φορέων επηρεάζεται από τις αρχικές γεωμετρικές ατέλειες και από τις παραμένουσες τάσεις μέλους, μεταξύ άλλων παραμέτρων. Η αξιοπιστία των κανονιστικών διατάξεων όσον αφορά στην ευστάθεια, αλλά και των προσομοιώσεων πεπερασμένων στοιχείων μεταλλικών μελών, εξαρτάται από την ακρίβεια των υπολογιζόμενων παραμενουσών τάσεων. Διαθέσιμα προσομοιώματα παραμενουσών τάσεων έχουν δημιουργηθεί με βάσει πειραματικά δεδομένα που πραγματοποιήθηκαν στις αρχές της δεκαετίας του 1950. Λόγω αυτού, συγκρίσεις με περίπου 80 διαθέσιμα πειραματικά δεδομένα που συλλέξαμε και συμπληρώσαμε με δικές μας πειραματικές δοκιμές σε μεταλλικές διατομές όπου δεν υπήρχαν διαθέσιμες μετρήσεις, δείχνουν ότι το διαθέσιμο Ευρωπαικό προσομοίωμα (ECCS) δεν είναι ακριβές. Στην παρούσα εργασία προτείνουμε ένα νέο προσομοίωμα παραμενουσών τάσεων που στηρίζεται σε μια μεθοδολογία βελτιστοποίησης της διαφοράς μεταξύ των συλλεγμένων μετρήσεων και των εξισώσεων δευτέρας τάξης που χαρακτηρίζουν τις παραμένουσες τάσεις. Ο μέσος όρος του σφάλματος μεταξύ του προτεινόμενου προσομοιώματος και όλων των διαθέσιμων πειραματικών μετρήσεων είναι μειωμένος κατά 70% σε σύγκριση με το υπάρχον Ευρωπαικό προσομοίωμα. Επιπλέον, η αντίστοιχη διασπορά μειώνεται κατά 300%.