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Residual stress distribution of large steel equal leg angles

Primož Može [a,*], Luis-Guy Cajot [b], Franc Sinur [a], Klemen Rejec [a], Darko Beg [a]

[a] Faculty of Civil and Geodetic Engineering, University of Ljubljana, Jamova 2, 1000 Ljubljana, Slovenia
[b] ArcelorMittal Belval & Differdange S.A., 66 Rue de Luxembourg, L-4009 Esch/Alzette, Luxembourg

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ABSTRACT

The market offers new large steel angle profiles, the largest being L300/35. To check their buckling resistance, the investigation of the residual stress field is presented in this paper. Since the buckling behaviour of steel angles is significantly affected by the residual stresses, the stresses were measured on six hot rolled and two welded equal angles by sectioning method. The traditional sectioning method was improved by introducing the water jet cutting. The released deformations were measured by the strain gauges. On the basis of the statistical evaluation of the test results, the most appropriate residual stress distribution models were considered in the numerical analysis. The results of the geometrical and material nonlinear numerical analysis were equal angle buckling curves.

1. Introduction

Buckling resistance is one of the main concerns of steel angles. The main parameters that define buckling resistance are residual stresses and geometrical imperfections. Buckling curves in Eurocode standard [1] that also apply to angles are based on the residual stress (RS) measurements conducted in Europe [2] in the 1970s. The 3-point linear RS distribution model as depicted in Fig. 1 was proposed in literature with different amplitudes [2–5] and is adopted in Eurocode [2]. The plus and minus sign in Fig. 1 correspond to tensile and compressive RS, respectively, while f_y stands for the steel yield stress and β_i factors define the RS amplitude.

The market offers new equal angle sizes with the largest angle size of L300/35 (nominal width/thickness of legs in mm) [6]. The leg length as well as the leg thickness affect the RSs. Moreover, the improved yield strength and the manufacturing process also influence the RSs. Therefore, an experimental program was launched to measure RSs in large equal angle profiles. RSs were measured on eight steel angle profiles manufactured by ArcelorMittal. Six of them were hot rolled, while two of them were welded. The two angles were welded by V-groove weld. The angles' dimensions are given in Table 1.

The measured values of residuals stresses were statistically analysed and several RS distribution models were included in the numerical model to obtain buckling resistance of angle profiles. The geometrical imperfections were also taken into account explicitly. The results of numerical parametric analyses were buckling curves for steel angle profiles.

2. Material characteristics of angle profiles

The material characteristics were measured by standard tensile tests according to EN ISO 6892-1 [7]. The round test pieces were extracted from the angle profiles as defined in EN ISO 377 [8], one test piece for each angle. The results of the tests are listed in Table 2 and illustrated in Fig. 2.

3. Residual stress measurements

3.1. General about measuring method

The residual stresses were measured in all angle profiles (see Table 1) by sectioning method. This method was chosen for several reasons. The main reason was that the RSs in the longitudinal direction have important effect on the buckling behaviour, while in the transverse direction RSs are of minor importance. The advantage of the sectioning measuring method is also high accuracy and relatively low cost compared to other measuring techniques (X-ray diffraction, ultrasonic method, hole-drilling method).

* Corresponding author. Tel.: +386 1 4768625; fax: +386 1 4768629.
E-mail addresses: primoz.moze@fgg.uni-lj.si (P. Može), Lg.cajot@arcelormittal.com (L.-G. Cajot), franc.sinur@fgg.uni-lj.si (F. Sinur), klemen.rejec@fgg.uni-lj.si (K. Rejec), dbeg@fgg.uni-lj.si (D. Beg).

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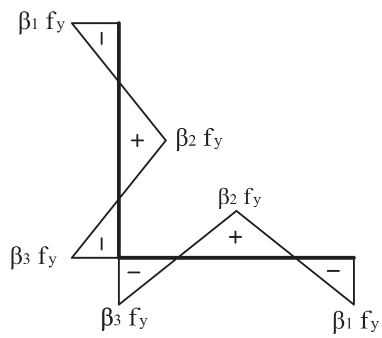

Fig. 1. Residual stress distribution model of hot rolled steel equal angles application in Europe [2]: $\beta_1 = -0.22$, $\beta_2 = 0.24$, $\beta_3 = -0.25$; application in the United States [3–5]: $-\beta_1 = \beta_2 = -\beta_3 = 0.30$.

Table 1
Angle profile dimensions (for hot rolled see also [6]).

Angle	Leg length, *b* (mm)	Plate thickness, *t* (mm)	*b*/*t*	Length (mm)	Type
L180/16	180	16	11.25	1800	Hot rolled
L180/19	180	19	9.47	1800	Hot rolled
L250/21	250	21	11.90	1800	Hot rolled
L250/28	250	28	8.93	1800	Hot rolled
L300/26	300	26	11.54	1800	Hot rolled
L300/35	300	35	8.57	1800	Hot rolled
L250/20	250	20	12.50	1800	Welded
L250/31	250	31	8.06	1800	Welded

The sectioning method is based on the principle that internal stresses are released by cutting the specimen strips of smaller cross-section. The stress distribution over a cross-section can be determined with reasonable accuracy by measuring the change in the length of each strip and by applying Hook's law. The analysis is further simplified by assuming that the transverse stresses are negligible and that the cutting process alone produces no appreciable strains. In practice, however, transverse stresses may exist, but the lower the transverse stresses are, the more accurate the results will be. The traditional cutting by saw may produce the RSs due to cutting alone. These disadvantages were avoided by introducing abrasive water jet cutting, which uses high velocity stream of abrasive particles suspended in a stream of high pressure water. The main benefits of this method are very high accuracy of cut positions (±0.2 mm), the cuts are about 2 mm thick and there is no interfering with the material's inherent structure as there is no heat-affected zone. From our experience [9] the maximum temperature during cutting does not exceed 50 °C. The maximum temperature is reached only for a short period of time due to friction between abrasive material and steel plate.

3.2. Preparation of test specimens and measuring protocol

The released strains were measured by waterproof strain gauges with 3 mm and 6 mm gauge lengths. These strain gauges have a pre-attached vinyl lead wire and an entire coating with epoxy resin. The coating is transparent and flexible. The gauges were installed to the angles according to the producer's installation manual. They were used in a Wheatstone bridge circuit with temperature compensation and were connected to two independent data acquisition systems, one for each angle leg.

The strain gauges were installed according to the water jet cutting plan. Both legs of the angle were equipped in total with 37–42 strain gauges, depending of the angle size. Each strain gauge, except two strain gauges near the angle heel and on the leg tip, had its pair on the opposite side of the leg. The cuts were 3 mm away from the coating of the strain gauge (see Fig. 3).

The cutting was performed in a workshop, equipped with professional water jet cutting tools. The strain measurements were taken through-out the cutting process. The cutting and measuring procedure followed the described steps. The test specimen was connected to the measuring devices and the measurements of strains were recorded. The initial value of strain was equal to zero, because the profile was not exposed to any external load. Next, the specimen was put on the cutting table. The angle was first cut in the transverse direction in two pieces (see left part of Fig. 4). After this cut most of the RSs relieved. The 40 mm long longitudinal cuts followed (see right hand side of Fig. 4) to relieve the remaining RSs. When the cutting was finished, the specimen was moved from the cutting table and the final measurements were taken at least 30 min later, when it dried and completely cooled to the room temperature.

During the sectioning process steel remained elastic. Because the difference in temperature was compensated within the Wheatstone bridge circuit, residual stress σ_r can be calculated directly from the measured residual strain ε by applying Hook's law:

$$\sigma_r = -E \cdot \varepsilon, \tag{1}$$

where E is elastic modulus. Nominal value of 210 GPa was adopted. The tensile RS (positive sign) corresponds to the contraction of gauge length (negative sign of ε). Therefore, the negative sign applies in Eq. (1).

The strains were measured on the inside ε_{in} and outside ε_{out} surface (see also part of Fig. 3). Thus, the average RS $\bar{\sigma}_r$ is calculated as the average of RS on the inside $\sigma_{r,in}$ and outside $\sigma_{r,out}$ surface:

$$\bar{\sigma} = \frac{\sigma_{r,in} + \sigma_{r,out}}{2} = -E\left(\frac{\varepsilon_{in} + \varepsilon_{out}}{2}\right). \tag{2}$$

The linear RS distribution over the leg thickness is assumed in Eq. (2). From the equilibrium it is clear that such approximation is reasonable.

Table 2
The results of standard tensile tests.

Angle	Diameter (mm)	Length (mm)	Yield stress, R_{eH} (MPa)	Tensile strength, R_m (MPa)	Elongation at fracture, A_t (%)	Reduction of area, *Z* (%)	Type	Steel grade
L180/16	9.91	50.00	447	559	29.4	70	Hot rolled	S420
L180/19	9.95	50.00	385	519	32.3	70	Hot rolled	S355
L250/21	9.98	50.00	397	537	32.3	71	Hot rolled	S355
L250/28	9.99	50.00	380	562	36.7	72	Hot rolled	S355
L300/26	9.92	50.00	394	562	29.5	71	Hot rolled	S355
L300/35	9.98	50.00	379	575	27.4	70	Hot rolled	S355
L250/20	9.99	50.00	285	395	38.1	73	Welded	S275
L250/31	9.98	50.00	499	590	24.1	69	Welded	S460