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Influence of samples location and orientation on hot-rolled structural steel mechanical properties: Experimental report

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ABSTRACT: For an accurate modelling of structures behavior, a precise determination of mechanical properties of structural steel is essential. Mechanical characterization must achieve standard prescriptions; thus, samples must be taken from a specific location and orientation, and the obtained properties from these specimens are used to characterize, uniquely, the steel. The hot-rolling process of structural steel profiles manufacture, which induces residual stresses distribution, can affects to homogeneity and isotropy of final product, therefore, uniformity of mechanical properties along the section is not guaranteed. The variation of these properties depending on orientation and location is studied in this paper. A tensile testing experimental program, where stress – strain curves are recorded and used to obtain mechanical properties at elastic and plastic conditions from different locations and orientations, have been carried out. No similar experimental work was found at literature, except in case of cold-bending formed steel. Results showed no significant differences for most cases, however properties related with necking and failure showed a clear dependence on location. Higher differences were found at specimens from the center of the flange. In addition, the research performed denotes that orientation has no influence on the variation of mechanical properties of hot-rolled steel.

KEYWORDS: Mechanical testing; Plastic deformation; Standard; Structural steel; Tensile properties

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RESUMEN: *Influencia de la ubicación y orientación de muestras en las propiedades mecánica del acero estructural laminado en caliente: Reporte experimental.* Para un modelado adecuado del comportamiento de las estructuras, es esencial una determinación precisa de las propiedades mecánicas del acero estructural. La caracterización mecánica debe satisfacer las prescripciones de las normas; en consecuencia, las muestras deben ser tomadas de una posición y orientación especifica; y las propiedades obtenidas de estos especímenes son usadas para caracterizar, de manera única, el acero. El proceso de laminado en caliente usado en la manufactura de perfiles de acero estructural, que implica la aparición de tensiones residuales, puede afectar a la homogeneidad e isotropía del producto final; por ello, la uniformidad de las propiedades mecánicas a lo largo de la sección no está garantizada. La variación de estas propiedades depende de la orientación y la locación y es estudiada en este artículo. Un programa de ensayos a tracción ha sido llevado a cabo, donde las curvas esfuerzo – deformación son registradas y usadas para obtener las propiedades mecánicas en condiciones elásticas y plásticas desde diferentes posiciones y orientaciones. No se encontraron trabajos experimentales similares en la literatura, excepto en el caso de acero conformado por doblado en frío. Los resultados no muestran diferencias significativas en la mayoría de casos; no obstante, las propiedades relacionadas con la estricción y falla muestran una clara dependencia con la ubicación. Las diferencias más importantes se hallaron en las muestras localizadas en el centro del ala; además, la investigación realizada denota que la orientación no influye en la variación de las propiedades mecánicas del acero laminado en caliente.

PALABRAS CLAVE: Acero estructural; Caracterización mecánica; Deformación plástica; Estándares; Propiedades en tracción

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1. INTRODUCTION

A fair determination of the mechanical properties of structural steel is essential for an accurate modeling of the behavior of a structure. Standards supply values for yield and ultimate strength for each type of steel, in conjunction with general values for the Young's modulus and the Poisson's ratio. These values are enough to carry out the structural design, however, values of other mechanical properties as: hardening modulus, fracture strength or fracture strain, which are required to predict the behavior under unusual load conditions, are not included at standards, and must be experimentally determined.

In Europe, two standards must be taken into account when designing the experimental program for determining such properties, i.e. ISO 377 (2017), which is used for location and preparation of specimens, and ISO 6892-1 (2016), which establishes the procedure for tensile testing. The ASTM A370-16 (2016) agrees with them for the most important issues. The first one assumes that, as a result of manufacturing process, steel products are heterogeneous, so the mechanical properties of samples from various locations can be different. Even more, in the case of hot-rolled beams, steel from webs and from flanges must be considered as different steels. According to this, specimens must be obtained from a specific location and orientation, depending on: the final use of the product (beams, bars, plates, etc.), the geometry and the thickness. Specimens must be located at the center of the piece and away from the edge, where properties can be disrupted by the manufacturing process. Orientation must be coincident with the shape rolling axis. This carries a significant material loss, as explained ahead in this paper.

Mechanical properties of steel can be used in different types of simulations, such as those using the Finite Element Method (FEM), or those obtained from theoretical or parametric models. FE software typically allows a complete description of the stress – strain curve, whereas theoretical and parametrical models commonly require, uniquely, the values of the main properties, as in Piluso *et al.* (2001) and Coelho *et al.* (2004). In all these simulations, it is assumed that the properties are the same at every point of the structure than those obtained by testing samples from a specific part.

Those main mechanical properties are obtained from engineering stress – strain curves, as coordinates of several significant points. ISO 6892-1 (2016), establishes the procedure for obtaining some of these properties. The remaining properties are usually obtained from true stress – strain curves, which can be drawn from the engineering one.

The aim of this paper is to determine the difference between mechanical properties of specimens obtained from different locations and orientations of the flanges of a structural steel hot-rolled beam. An experimental program consisting of tensile testing of specimens from different locations, orientations and cross-section has been carried out. Strain gages have been used to obtain accurate strain measurements. The stress – strain curves (engineering and true) have been represented, and mechanical properties were obtained and compared from these curves. Results are not homogeneous and some interesting conclusions are drawn below.

2. MATERIALS AND METHODS

2.1. Basis & standards prescriptions

A stress-strain curve can be described by a few essential points and slopes where trend changes. Specifically, these points are (Fig. 1):

A. End of elastic behavior, which is defined by yield strength f_y (stress at point A) and Young Modulus E (slope of line 0-A). Determination of f_y is typically done by means of the 0,2% offset method.
B. End of yielding, usually estimated as a flat behavior, defined by means of strain at the beginning of hardening ε_h (strain at B).
C. End of strain hardening, or maximum load point, usually defined by ultimate strength f_u and ultimate strain ε_u, and also by means of the hardening modulus E_h (average slope of section B-C).
D. Fracture, defined by fracture strength f_f and fracture strain ε_f (coordinates of D). Necking phase is defined by means of the necking modulus E_u (average slope of section C-D).

These properties are obtained from the engineering stress-strain curve, however, several approaches

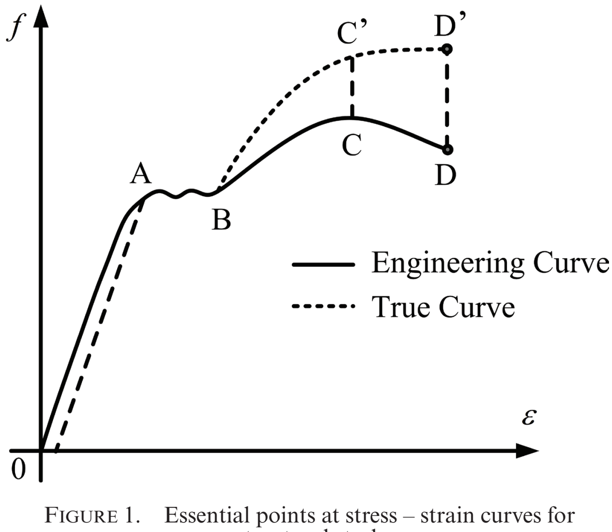


FIGURE 1. Essential points at stress – strain curves for structural steel.

(Piluso *et al.*, 2001; Coelho *et al.*, 2004) uses values obtained from the true stress – strain (C' and D' shown at Fig.1). True stress-strain curves can be drawn from engineering curves by applying Nadai's equations (Nadai, 1933):

$$f_t = f(1+\varepsilon); \quad \varepsilon_t = \ln(1+\varepsilon) \qquad (1)$$

where f_t and e_t are stress and strain at the true curve obtained from f and ε at the engineering curve.

For commonly used structural steels, reference values of these properties can be found at literature (Kato *et al.*, 1990; Gioncu and Mazzolani, 2002). These values have been summarized at Table 1. Also, the ISO 6892-1 (2016), defines additional properties related to the specimen dimensions after failure, actually:

- The percentage elongation after fracture A, is defined as the permanent elongation of the gauge length after fracture, expressed as a percentage of the original gauge.
- The percentage reduction of area Z, is defined as the maximum change in cross-sectional area which has occurred during the test, expressed as a percentage of the original cross-sectional area.

However, structural steel must meet the requirements of the corresponding national regulation in terms of elastic limit and resistance. In Europe, most countries apply values suggested at Eurocode 3 (EN 1993-1-1, 2005). which also depend on the nominal thickness of the element. As ductility requirements, the Eurocode 3 (EN 1993-1-1, 2005) recommends these conditions for f_u and ε_u:

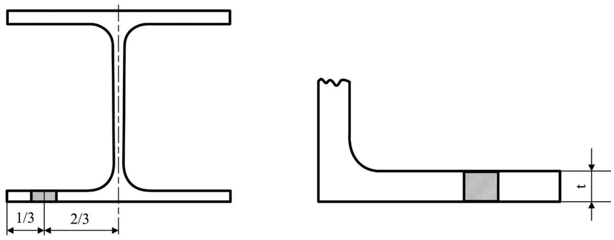
$$\begin{cases} f_u / f_y \geq 1.10 \\ \varepsilon_f \geq 15\% \\ \varepsilon_u \geq 15\varepsilon_u \end{cases} \qquad (2)$$

Design values for Young's modulus and Poisson's ratio are also shown, but no conditions to other properties like hardening strain ε_h, hardening modulus E_h, necking modulus E_u or fracture stress f_f are established at Eurocode 3 (EN 1993-1-1, 2005).

ISO 377 (2017) establishes that, for flange rolled beam steel, location of samples across the width of section must be 1/3 away from edges and 2/3 away from center of section, as shown in Fig. 2a. About the location in thickness of section, full thickness samples must be used (Fig. 2.b). Given that circular or rectangular cross-section test pieces can be machining from these samples, only the rectangular one will finally keep the full thickness, so cross-section may also have some influence on results, as discussed by RILEM (1990) orientation of test tubes must be the same as shape rolling axis. The influence of these prescriptions on the mechanical properties has been highlighted as the main subject of this research.

The hot rolling manufacturing process results in a recrystallization of steel, which might happen in static or dynamic conditions, and with temperature playing a very important role. Cooling rate along shape rolling axis is lower than along radial direction; thus, grain growth is not isotropic, mainly in the presence of some elements such as Nickel or Chromium (Llewellyn and Hudd, 1998; Lenard *et al.*, 1999). However, hot rolling is not a strengthening process itself, therefore great differences at mechanical properties values are not expected.

Test tube locations are chosen by the standard look away from areas prone to unrepresentative defects such as edge defects, in order to improve the quality of the sample's representation. Moreover, the manufacturing process is affected by several chemical, mechanical and thermal parameters; thus, some mechanical property predictions models were proposed considering these parameters (Zhao *et al.*, 2013), although no experimental studies about the



a) b)

FIGURE 2. Location of test pieces across the width of section (a) and in thickness of section (b) from (ISO 377, 2017).

TABLE 1. Mechanical properties reference values for structural steels from (Kato *et al.*, 1990; Gioncu and Mazzolani, 2002)

Steel	f_y [N·mm^{-2}]	f_u [N·mm^{-2}]	ε_y [%]	ε_h [%]	ε_u [%]	ε_f [%]	E_h [N·mm^{-2}]	E_u [N·mm^{-2}]
S235	235	360	0.115	1.41	14.0	25.0	5500	360
S275	275	430	0.134	1.47	12.0	22.0	4800	430
S355	355	510	0.173	1.70	11.0	20.0	4250	510

influence of location and orientation have been found. Similar works have been previously carried out by Spoorenberg *et al.* (2012), in the field of cold-bending formed steel.

2.2. Experimental program

In order to verify if ISO 377 (2017) prescriptions about location of samples have any influence on the mechanical properties, forty-two test tubes were tensile strength tested, obtaining significant readings for thirty-six of them, and dismissing the results of six due to out of range results. Variables of interest are: location across the width, orientation and cross-section shape.

Four different location/orientation and two different shapes of specimens were selected, as detailed in Table 2 and Fig. 3. All of them were obtained from the flanges of an HEB400 beam of S275 structural steel. Dimensions of specimens are shown at Fig. 4. These dimensions are chosen to meet ISO 6892-1 (2016) requirements.

The preparation of specimens is carried out in two main phases: First, the right prism from the flanges of the beam with the location and orientation intended is obtained by wheel sawing, band sawing and oxycutting. Later, the bone shape with the final dimensions is achieved by using numerical control milling and turning, which also serves to remove the oxycutting heat affected zone. Final dimensions of specimens meet tolerance limits indicated at ISO 6892-1 (2016).

Obviously, steel properties are related to constituent elements and their percentage. In the case of structural steels, standard values are used to establish percentage limits or range for each element.

Before tensile testing of the specimens, an inductively coupled plasma mass spectrometry (ICP-MS) was used in order to obtain the steel composition and verify compliance with the standard. Six samples were prepared following the ISO 14284 (1996) and results (Table 3) showed that Carbon, Nitrogen, Hydrogen and Sulfur contents meet the EN 10025-2 (2004).

Post-yield foil strain gages are employed to perform strain measurements, due to their high accuracy. A cyanoacrylate adhesive (CN-Y, Tokyo Sokki Kenkyujo Co.) is used, since it is suitable for post-yield behavior. Finally, strain was read from the gages by a P3 Strain Indicator (Vishay Micro-Measurements Co.-Wendell, NC, USA).

Tensile testing was carried out using a MTS 810 loading machine, of 100 kN load capacity. Load was applied at the rate of 0.5 mm·min^{-1}, within the range suggested by standard. Extensometers were also used to validate strain gages measurement.

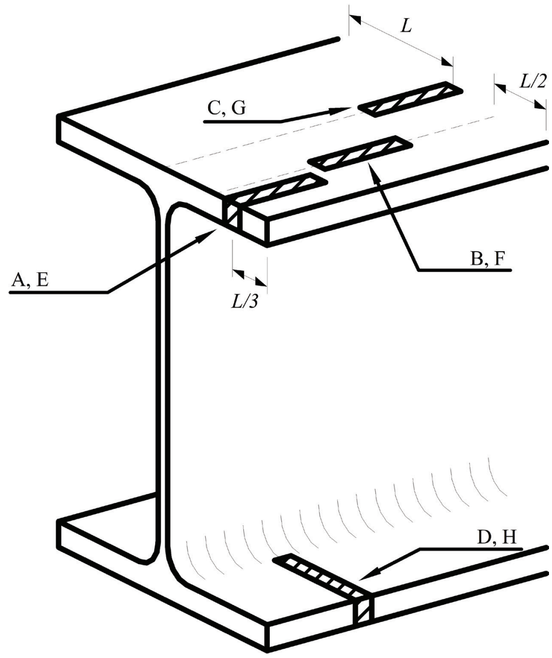


FIGURE 3. Location of specimen batches: A. B. C and D with rectangular cross-sections and E. F. G y H with circular cross-sections.

TABLE 2. Description of tested specimens and corresponding batch (amount of specimens between brackets)

Specimens	Cross-section	Location / orientation	Batch ID
Total (36)	Rectangular (18)	At L/3 (5)	A
		At L/2 (4)	B
		At L (in the center) (4)	C
		Transverse orientation (5)	D
	Circular (18)	At L/3 (4)	E
		At L/2 (4)	F
		At L (in the center) (4)	G
		Transverse orientation (6)	H

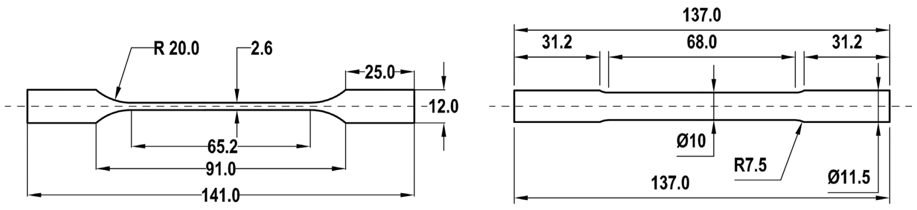


FIGURE 4. Dimensions of specimens with rectangular (a) and circular (b) cross-section (mm).

TABLE 3. Steel chemical composition obtained with ICP-MS

Sample	Nitrogen %	Carbon %	Hydrogen %	Sulfur %
1	0.0096	0.1123	0.0036	0.0099
2	0.0076	0.1159	0.0023	0.0084
3	0.0026	0.1101	0.0032	0.0000
4	0.0021	0.1016	0.0029	0.0000
5	0.0015	0.0962	0.0016	0.0000
6	0.0016	0.0935	0.0016	0.0000
average	***0.0042***	***0.1049***	***0.0025***	***0.0030***

3. RESULTS

Stress-strain curves have been drawn for each specimen tested based on readings from strain gages and load cells.

These curves are shown at Fig. 5. Also, average curves were obtained for each batch by applying regression to three separate portions of the curves, as follows:

- Linear regression at the elastic region ($y = Ex$, where E is the Young modulus).
- 6th degree polynomial regression at yielding ($y = ax^6 + bx^5 + cx^4 + dx^3 + ex^2 + fx + g$), and also,
- 6th degree polynomial regression at the plastic region.

Average coefficients for regressions at elastic, yielding and plastic regions are shown at Table 4 for each batch. A minimum correlation factor of 0.99 was set as objective when performing the regression analysis for each specimen. After several attempts, 6th degree functions are required to achieved the desired correlation factor.

Finally, mechanical properties have been obtained for each specimen, and average values and standard deviation σ calculated for each batch of specimens. Results are shown at Table 5. Properties are divided into three categories:

- Basic properties, which are acquired from the engineering stress – strain curves.
- True properties, obtained from the true stress – strain curves, drawn by using *Eq.* (1).
- Standard properties, as defined at ISO 6892-1 (2016) and related to specimen dimensions after failure.

4. DISCUSSION

The results listed in Table 5 and illustrated in Fig. 5 exhibit a high degree of similarity. However, a detailed comparison of average curves and calculated properties is required in order to identify differences due to location, orientation and cross-section of test tubes along the flange of the beam.

A first comparison between results obtained at the same location and orientation, but with different cross-sections is carried out. Hence, results from batches A (rectangular) and E (circular) are compared. Both batches are located at L/3 from the edge of the flange and follow standard prescriptions about location and orientation. Figure 6 shows A and E batches average curves and Table 6 has a comparison of calculated properties for each batch. Only properties related with necking and failure conditions show significant differences. Standard deviation values show that most properties values are steady, except necking modulus E_u. The obtained mechanical properties meet the Eurocode 3 (CEN/TC 250 (EN 1993-1-1, 2005)) requirements related to f_y, f_u and Eq. (2). Values are also similar to those cited at Table 1 from bibliography, except in case of hardening modulus E_h and necking modulus E_u. The hardening modulus E_h is far away from the values reported at Table 1, and results show a E_h close to 0.35 times the given value at references. The necking modulus E_u obtained for rectangular specimens is only a 1,4% away from the value of Table 1, however, the one obtained for circular cross-section specimens has a much higher difference.

Comparison of the remaining batches is performed taking the average values of A and E batches as reference. Differences are shown in Table 7, where it can be seen that, for rectangular cross-section specimens (batches B, C and D), the differences are maintained below about 10%, except for three values: strain at hardening ε_h, necking modulus E_u and percentage reduction of area Z. Figure 7 shows the stress-strain curves for all these batches. It can be seen that the curve obtained for the middle of the

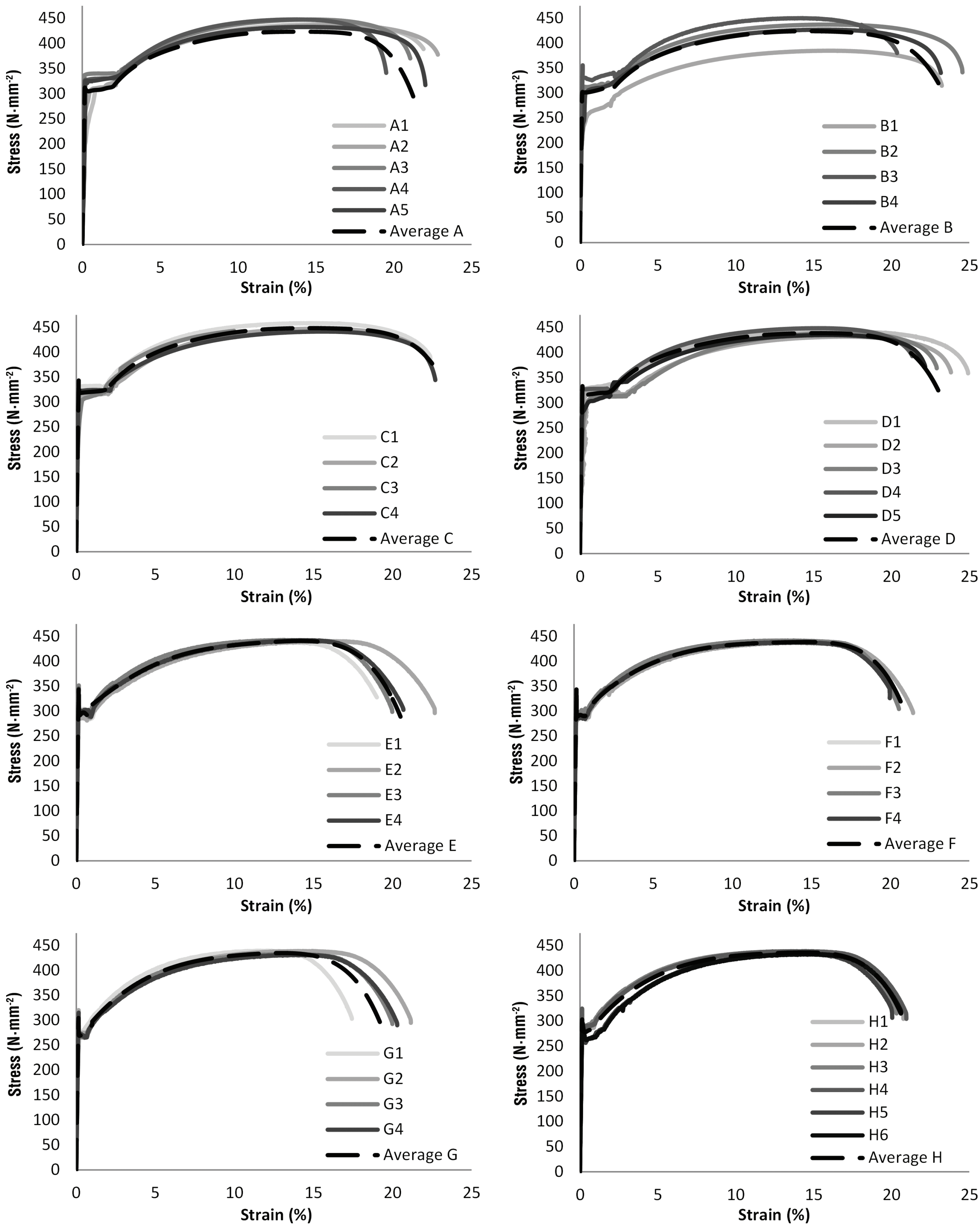


FIGURE 5. Stress – strain curves obtained for each specimen. and average curves (dashed lines) calculate per batch.

TABLE 4. Regression coefficients for batch average stress – strain curves

		Batch							
		A	**B**	**C**	**D**	**E**	**F**	**G**	**H**
Yielding	a	36.86	-0.63	0.02	-10.36	2768.77	5228.53	4106.48	-623.70
	b	-295.41	-3.07	4.53	85.31	-10057.76	-17729.41	-15055.94	1830.91
	c	949.01	26.92	-21.55	-272.83	15078.15	24137.95	21516.67	-1538.23
	d	-1555.07	-61.84	39.53	435.32	-11664.48	-16644.51	-15094.05	-143.51
	e	1364.02	66.30	-35.09	-367.80	4730.60	6016.82	5429.46	788.88
	f	-600.51	-28.09	17.89	161.23	-912.46	-1056.40	-942.48	-348.52
	g	424.64	305.15	315.48	287.75	357.49	359.89	331.17	324.26
Plastic	a	-1,00E-04	-6,07E-05	-5,68E-05	-6,54E-05	-1,63E-05	-6,81E-05	-4,79E-05	-5,39E-05
	b	8,80E-03	4,25E-03	3,98E-03	4,84E-03	1,21E-04	3,53E-03	1,90E-03	2,72E-03
	c	-2,33E-01	-1,21E-01	-1,14E-01	-1,46E-01	1,18E-02	-7,32E-02	-3,26E-02	-5,68E-02
	d	3.22	1.82	1.72	2.33	-0.20	0.84	0.41	0.70
	e	-25.28	-15.75	-15.19	-21.24	-0.41	-6.84	-5.08	-6.69
	f	116.75	83.28	83.06	114.13	26.88	45.79	45.45	49.49
	g	156.65	188.18	206.84	123.42	286.93	270.43	256.56	250.63

TABLE 5. Mechanical properties obtained for every specimen. and batch's average values

	Basic properties				True properties					Standard properties	
	E	f_y	f_u	ε_h	E_h	ε_u	f_f	ε_f	E_u	A	Z
		[N·mm^{-2}]		[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[%]
A1	200834	232	438	1.51	1300	17.00	474	19.81	474	21.91	40.23
A2	197677	284	436	1.39	1141	17.45	464	20.56	464	22.83	39.08
A3	247546	339	448	1.62	1309	15.79	448	19.11	448	21.06	43.55
A4	211931	328	448	1.83	1421	14.83	408	17.83	408	19.51	37.62
A5	212090	270	433	1.50	1183	16.39	387	19.91	387	22.03	44.38
$\bar{A}$	**214016**	**291**	**441**	**1.57**	**1271**	**16.29**	**436**	**19.44**	**436**	**21.47**	**40.97**
σ_A	**9.27%**	**15.0%**	**1.6%**	**10.6%**	**8.7%**	**6.3%**	**8.5%**	**5.3%**	**8.5%**	**5.9%**	**7.1%**
B1	185567	242	385	1.64	1061	17.52	388	20.89	-1953	23.06	43.14
B2	214217	312	437	1.71	1255	18.22	426	21.96	-2457	24.39	40.57
B3	194330	276	450	1.63	1467	14.12	453	17.47	-1866	20.16	43.98
B4	235742	293	427	1.39	1190	17.31	419	20.84	-2354	23.02	44.18
$\bar{B}$	**207464**	**281**	**425**	**1.59**	**1243**	**16.79**	**422**	**20.29**	**-2158**	**22.66**	**42.97**
σ_B	**10.8%**	**10.6%**	**6.6%**	**8.8%**	**13.6%**	**10.9%**	**6.3%**	**9.6%**	**-13.5%**	**7.9%**	**3.9%**
C1	204943	332	459	1.45	1194	16.79	474	20.20	-1815	21.98	44.54
C2	197491	282	447	1.58	1398	16.82	471	20.09	-1630	22.06	43.80
C3	209935	299	443	1.31	1669	9.51	-	-	-	-	-
C4	212828	322	442	1.67	1193	16.91	423	20.46	-2685	22.54	39.77
$\bar{C}$	**206299**	**309**	**448**	**1.50**	**1364**	**15.01**	**456**	**20.25**	**-2043**	**22.19**	**42.70**
σ_C	**3.3%**	**7.3%**	**1.7%**	**10.4%**	**16.5%**	**24.4%**	**6.3%**	**0.9%**	**-27.6%**	**1.4%**	**6.0%**
D1	209256	328	443	1.91	1220	18.41	448	22.25	-2047	24.74	45.96
D2	173588	288	432	-	1318	18.15	447	21.36	-2053	23.61	47.78
D3	185799	287	439	1.59	1308	17.49	453	20.62	-2099	22.71	41.37
D4	213740	327	449	1.46	1400	16.52	477	19.34	-1681	21.15	39.99
D5	232174	289	435	1.72	1290	17.17	454	20.02	-2042	22.00	37.87

Table 5. (Continued) Mechanical properties obtained for every specimen. and batch's average values

	Basic properties				True properties					Standard properties	
	E	f_y	f_u	ε_h	E_h	ε_u	f_f	ε_f	E_u	A	Z
		[N·mm^{-2}]		[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[%]
$\bar{D}$	**202911**	**304**	**440**	**1.67**	**1307**	**17.55**	**456**	**20.72**	**-1984**	**22.84**	**42.59**
σ_D	**11.5%**	**7.1%**	**1.5%**	**11.5%**	**4.9%**	**4.3%**	**2.7%**	**5.5%**	**-8.6%**	**6.1%**	**9.7%**
E1	216351	296	438	1.12	1644	14.04	390	17.40	-3309	20.50	45.79
E2	214669	290	441	1.02	1419	16.37	364	20.43	-3766	20.75	67.30
E3	217252	301	443	1.04	1365	14.70	358	18.21	-4311	28.75	68.32
E4	210939	300	443	1.13	1459	14.74	365	18.80	-3581	20.25	66.37
$\bar{E}$	**214803**	**297**	**441**	**1.08**	**1472**	**14.96**	**369**	**18.71**	**-3742**	**22.56**	**61.95**
σ_E	**1.3%**	**1.7%**	**0.5%**	**5.2%**	**8.2%**	**6.6%**	**3.8%**	**6.9%**	**-11.3%**	**18.3%**	**17.4%**
F1	212435	295	438	0.94	1731	15.30	-	-	-	-	-
F2	207123	288	440	0.96	1531	15.43	360	19.43	-3735	52.50	67.23
F3	218752	296	442	1.03	1414	15.46	637	18.68	-4478	29.00	66.88
F4	220152	287	439	0.97	1296	15.07	414	18.21	-2959	30.00	56.15
$\bar{F}$	**214616**	**292**	**440**	**0.98**	**1493**	**15.32**	**470**	**18.77**	**-3724**	**37.17**	**63.42**
σ_F	**2.8%**	**1.6%**	**0.4%**	**4.0%**	**12.4%**	**1.2%**	**31.2%**	**3.3%**	**-20.4%**	**35.8%**	**9.9%**
G1	192057	274	440	-	1895	12.87	356	16.06	-4417	29.00	66.53
G2	215994	273	439	1.01	1654	15.20	358	19.19	-3774	33.50	67.43
G3	212979	267	433	0.84	1430	14.75	351	18.22	-4225	33.50	66.25
G4	212125	272	432	0.96	1451	14.63	349	18.48	1451	28.75	67.09
$\bar{G}$	**208289**	**272**	**436**	**0.94**	**1608**	**14.36**	**354**	**17.99**	**-2741**	**31.19**	**66.83**
σ_G	**5.3%**	**1.1%**	**0.9%**	**9.3%**	**13.5%**	**7.1%**	**1.2%**	**7.5%**	**-102%**	**8.6%**	**0.8%**
H1	210229	284	437	1.04	1330	15.53	373	18.88	-3967	54.75	63.49
H2	220176	284	438	1.06	1378	15.40	368	18.87	-3971	32.00	64.34
H3	209550	287	439	0.93	1372	15.04	379	18.50	-3642	64.50	64.41
H4	212675	285	439	1.07	1260	15.22	368	19.02	-3687	28.75	64.34
H5	209412	261	434	1.35	1689	14.82	368	18.27	-3829	26.00	63.77
H6	206335	267	434	1.19	1654	15.15	381	18.75	-3369	30.00	63.84
$\bar{H}$	**211396**	**278**	**437**	**1.11**	**1447**	**15.19**	**373**	**18.72**	**-3744**	**39.33**	**64.03**
σ_H	**2.2%**	**4.0%**	**0.5%**	**13.1%**	**12.4%**	**1.7%**	**1.6%**	**1.5%**	**-6.1%**	**41.0%**	**0.6%**

flange (batch C) are the least approaching the reference curve of standards (batch A), similar to conclusions with cold-bending formed steel (Spoorenberg *et al.*, 2012).

Similar differences can be found when analyzing results obtained for circular cross-section specimens (batches F, G and H), although, in this case, the percentage elongation after fracture A also shows differences over 20%. Figure 8 shows the curves for all circular cross-section batches. Again, the least approaching the reference curve is the specimen from the center of the flange (batch G).

Finally, results obtained from specimens with transverse orientation (batches D and H) do not show a differentiated behavior from those specimens with longitudinal orientation. Further work about the isotropy of hot rolled steel is required, since the confirmation of this premise can generate a very important material saving, which can reach 80%, as performed in this study. Figure 9 shows the HEB400 beam flanges ready for longitudinal and transverse samples extraction, where the difference in the length of beam required for obtaining the specimens can be seen.

5. CONCLUSIONS

– A total amount of 42 specimens with different locations, orientations and cross-sections, have been tensile-tested in order to quantify the variation of eleven mechanical properties. Experimental data have been used to draw

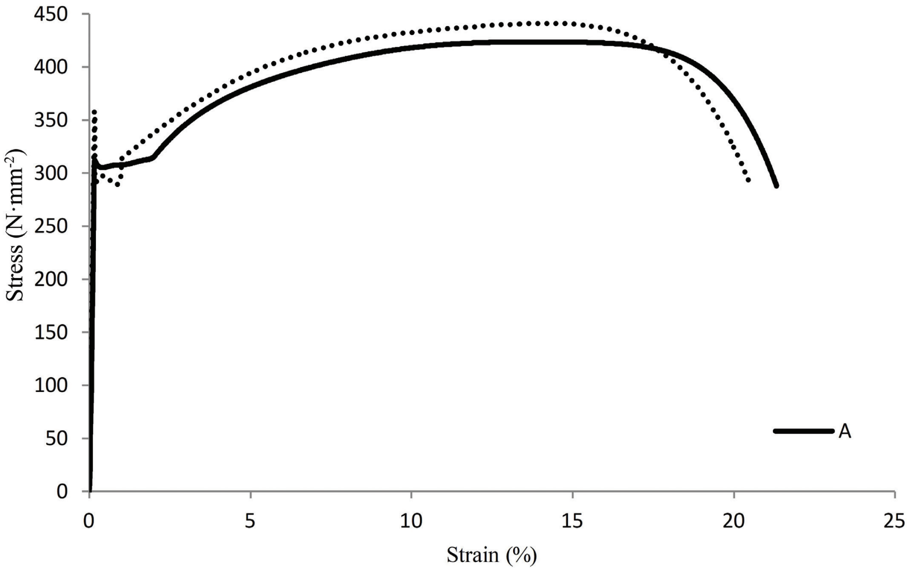


FIGURE 6. Stress – strain average curves comparison for batches A and E.

TABLE 6. Mechanical properties comparison for A and E batches

	Basic properties				True properties					Standard properties	
	E	f_y	f_u	ε_h	E_h	ε_u	f_f	ε_f	E_u	A	Z
	[N·mm^{-2}]	[N·mm^{-2}]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[N·mm^{-2}]	[%]	[%]
$\bar{A}$	214016	291	441	1.57	1271	16.29	436	19.44	436	21.47	40.97
σ_A	9.27%	15.0%	1.6%	10.6%	8.7%	6.3%	8.5%	5.3%	8.5%	5.9%	7.1%
$\bar{E}$	214803	297	441	1.08	1472	14.96	369	18.71	-3742	22.56	61.95
σ_E	1.3%	1.7%	0.5%	5.2%	8.2%	6.6%	3.8%	6.9%	-11.3%	18.3%	17.4%
$\overline{AE}$	**214409**	**294**	**441**	**1.32**	**1371**	**15.63**	**403**	**19.08**	**-1653**	**22.02**	**51.46**
σ_{AE}	0.3%	1.5%	0.1%	26.3%	10.4%	6.0%	11.8%	2.7%	-178%	3.5%	28.8%

TABLE 7. Percentage differences founded in mechanical properties per batch. using AE mean values as reference

	Basic properties				True properties					Standard properties	
	E	f_y	f_u	ε_h	E_h	ε_u	f_f	ε_f	E_u	A	Z
D*if*.$\bar{B}-\overline{AE}$	-3.2	-4.4	-3.7	20.3	-9.3	7.5	4.7	6.4	30.5	2.9	-16.5
D*if*.$\bar{C}-\overline{AE}$	-3.8	5.1	1.5	13.5	-0.6	-4.0	13.2	6.1	23.6	0.8	-17.0
D*if*.$\bar{D}-\overline{AE}$	-5.4	3.4	-0.3	26.2	-4.7	12.3	13.2	8.6	20.1	3.8	-17.2
D*if*.$\bar{F}-\overline{AE}$	0.1	-0.7	-0.3	-26.3	8.9	-2.0	16.8	-1.6	125.3	68.8	23.2
D*if*.$\bar{G}-\overline{AE}$	-2.9	-7.6	-1.1	-29.2	17.2	-8.1	-12.2	-5.7	65.9	41.7	29.9
D*if*.$\bar{H}-\overline{AE}$	-1.4	-5.3	-0.9	-16.4	5.5	-2.8	-7.4	-1.9	126.5	78.7	24.4

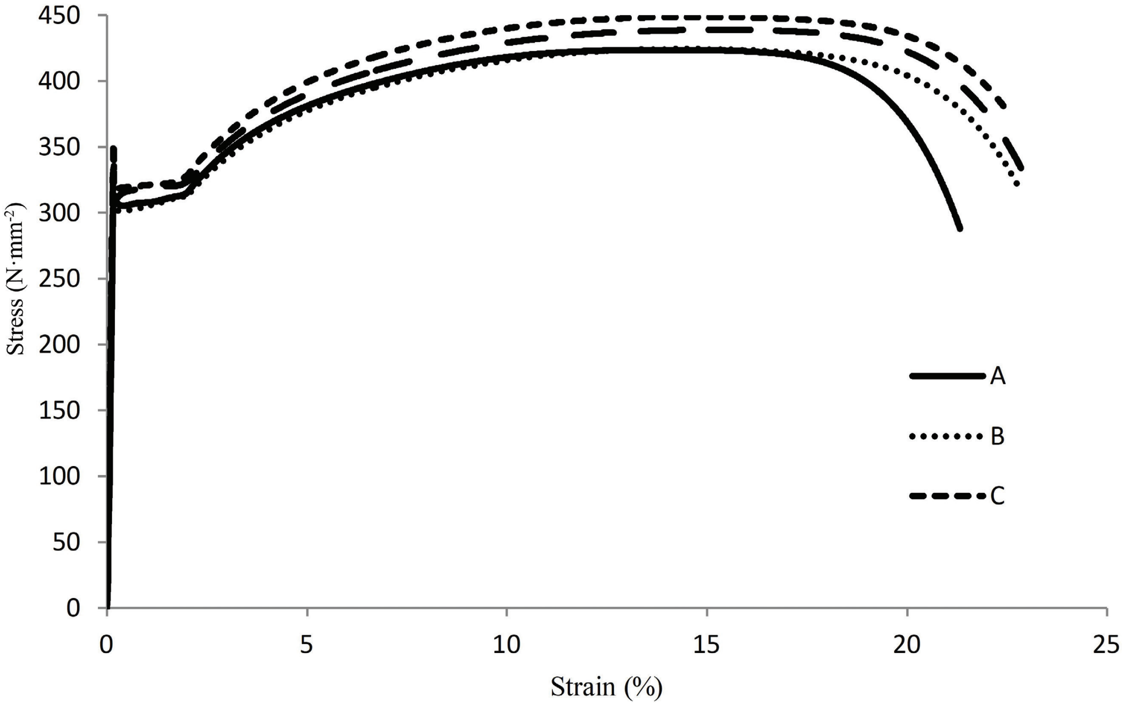


FIGURE 7. Stress – strain average curves comparison for batches with rectangular cross-section A. B. C and D.

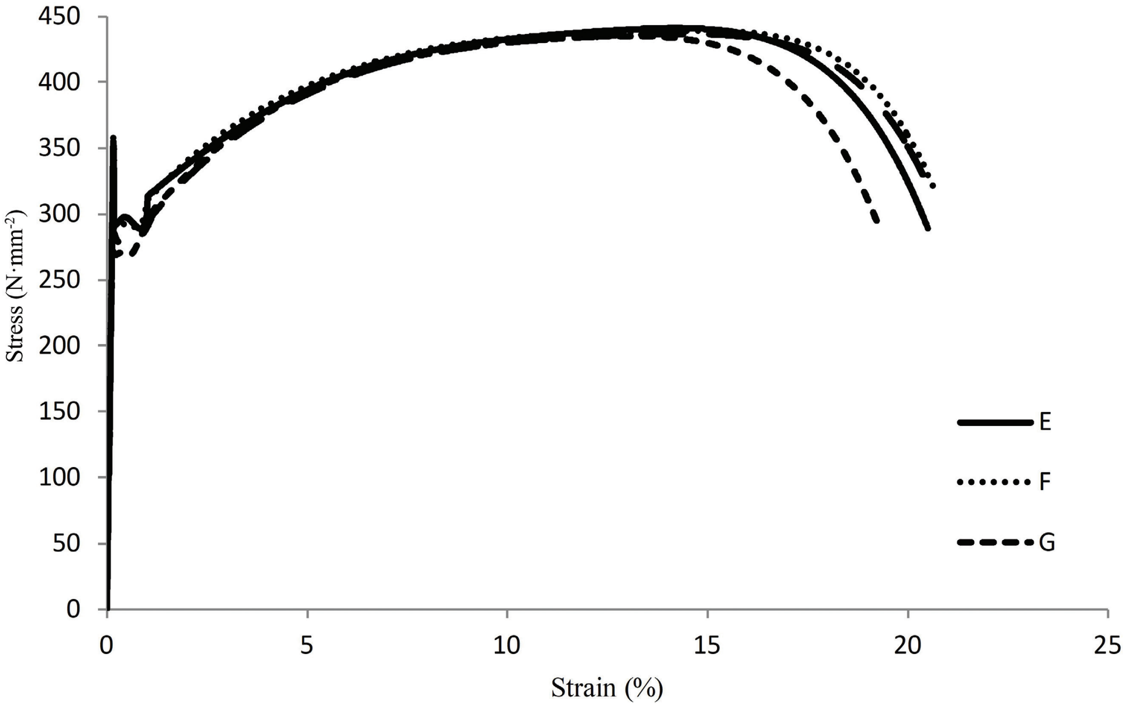


FIGURE 8. Stress – strain average curves comparison for batches with circular cross-section E. F. G and H.

engineering and true stress - strain curves for every specimen tested. Batch average curves have been obtained by means of three polynomic regressions (applied to three parts of the curve). Average curves and values were finally used for discussion of experimental results.

– Most curves compared are very similar and the main differences are shown at necking and

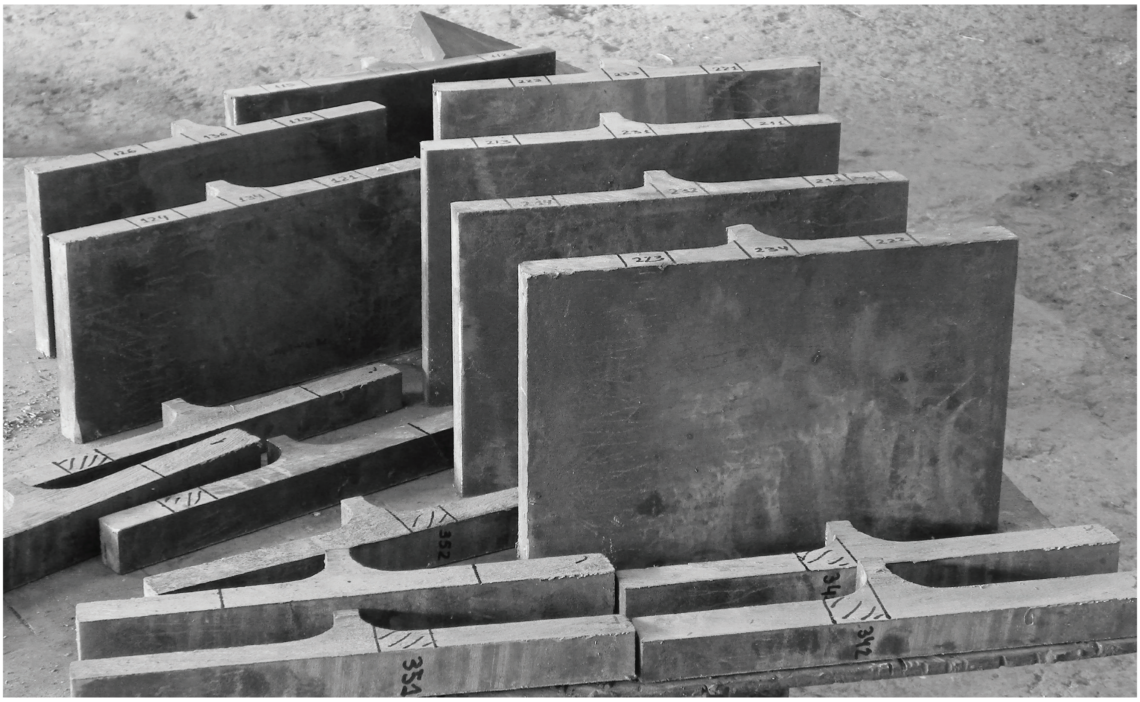


FIGURE 9. Beam flanges ready for longitudinal and transverse samples extraction.

failure behavior. Specimens extracted from the middle of the flange less approaches reference curves (at L/3, as standard states). Mechanical properties values are very similar in most cases, except for necking modulus E_u. About differences between cross-sections, rectangular and circular specimens also differ in percentage reduction of area Z and strain at hardening ε_h. Specimens with transverse orientation do not show significant differences from the reference, so the isotropy of steel is not very affected by the manufacturing process. The obtained mechanical properties achieve the Eurocode 3 CEN/TC 250 (EN 1993-1-1, 2005) prescriptions and are also similar to those found at literature.

– Despite limitations of experimental program, it can be said that mechanical properties of a structural steel do not change significantly for different locations and orientation than those state at standard. Main differences were found at the middle of the flange, and for necking and failure properties.

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