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"U" TYPE FOLDED STRUCTURAL PROFILE UNDER THE INFLUENCE OF DISTORTION DUE TO THE MAG WELDING PROCESS

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Abstract: *In the industrial field of metallic structures, CSN-CIVIL-300 steel plates are widely used. Now, to obtain quality structural products, two elements must be within reliable limits, in the elaboration of the dimensional project: the development of the plates and the geometry of the profile. This study focuses on the geometric variation of the structural profile section produced by distortions arising from residual stresses, which, in the U-type bent structural profile, are susceptible to deformations. Thus, this work aims to present a method for this analysis, called the laser scanning technique focusing on the welding process MAG, with the use of the Motoman UP6 robotic arm, regarding the behavior of structural steel in relation to distortion on the soldered joint. In view of this, the U-type folded plate steel profile 100x50x3.04 mm was applied to the MIG/MAG welding process, in a butt joint, using the AWS ER70S-6 electrode wire in the horizontal position 2g. In this process, four types of experimental joints were used (with and without bridges), gas protection of 75%Ar-25%CO2, and welding parameters that allowed keeping the current density constant. The conventional method of measuring the dimensions of the reference samples was used. It was verified that the calculated nominal stress is guaranteed with a gap of 8%, while the lowest resistance is registered in the HAZ making the material with a deficiency of 6.5%, concluding that 97% of the analyzed bent profiles broke at a characteristic point.*
Keywords: *Project; Folded sheet; Metallic structures; Manufacturing process.*

1. INTRODUCTION

The steel structure manufacturing and assembly industries widely use structural steel profiles in cold-formed, bent sheet metal, which are produced by several companies dedicated exclusively to the sheet metal bending process due to their mechanical resistance. In this process, two factors must remain with low variability and within reliable limits: the development of the plate to be cut for the bending process and the geometric shape of the bent section, standardized in relation to the area and inertia of the section that determine the structural projects (SACCHI, 2016).

In this sense, the selection by the GMAW (Gas Metal Arc Welding) welding process and exclusively MAG (Metal Active Gas), integrated to a Motoman UP6 robotic arm, effectively represents this type of event, inside the factories.

The production lines require the process of cutting and bending the sheet metal, the raw material for the structural elements, performed by machinery equipped with a cleaver, providing quality to the creases of the profiles (VERGILIO, 2011), which is another justification for its current use.

Thus, metallic profiles are specified in structural projects, in order to guarantee the safety of the building. However, any change in the mechanical characteristics of the steel should be rigorously inspected, in order to facilitate the fitting and positioning of the parts, without compromising the continuation of the work (SOARES, 2006).

Concomitantly with the bending of the structural profile, the manufacturing defects amplify the internal stresses introduced by the microstructural hardening added to the residual stresses due to the welding process, mainly in the formed place (RIBEIRO, 2010).

This type of metallic profile, when subjected to the welding process, corresponds to behavior with the appearance of deformations and warping arising from the residual stresses inserted in the process that totally depend on the welding parameters (AMARAL, 2022).

The influence of distortion on the folded structural profile can occur in several ways, mainly due to the direction of welding and the heat input into the part. As distortion it is a set of translations and rotations, the bent profile restricts displacements and rotations in planes and axes with their own rigidity (Pereira, 2020).

The folded regions, due to the cold work applied in the bending, raise the flow threshold by around 50%, a significant value that makes it less tenacious and harder. In cross-section design, these regions have modified degree of homogeneity with peculiar microstructural isotropic characteristics (BORGES; LINS, 2018).

In addition, the inertia of the profile has considerable inconstancy, which is unfavorable to the design, since the geometric centroid varies, making the stress distribution unconfigured along the profile, making it susceptible to localized buckling, depending on the external stresses that act, compromising the resistance. Because of this, periodic inspections of metallic structures are recommended (PEREIRA, 2018).

Certainly, the misalignment of the geometric center of the cross section in critical situations arises from efforts that generate bending moments, requiring monitoring at specific points to avoid structural collapse (ANTUNES, 2010).

In these circumstances, any present crack subjected to the cyclical actions of varying external forces can lead to fatigue of the material and in the bends of the profile, it can have a deleterious role, since it boosts the stress, concentrating it in a localized way. The establishment of stress concentrators, at relatively isolated points, becomes the driving force to develop the collapsible phenomenon with imperceptible deformations (CORDEIRO, 2018).

Based on these assumptions, this work presents the behavior of the bent metallic profile in the face of punctual displacements promoted by the welding process and the verification of the mechanical resistance.

2. MATERIALS AND METHODS

2.1 Materials

Over the last 20 years, companies from different countries that met the assumptions of a certain statistical dimensional control were selected, based on a standard deviation using the Student Method. Of the 22 companies, two were selected, from which samples were acquired.

Wire electrodes, in AWS ER70S-6 specifications, with diameters, sequentially, of 0.9 and 1.0 mm, were used as filler metals. In all welds, gas protection was performed by mixing 75% Ar - 25% CO2, at a flow rate of 2.1. 10 - 4 m3. s - 1 (12.5 l. min - 1).

In order to represent what happens in the cutting and bending sectors of the metallic profiles, a CSN-CIVIL-300 structural steel coil was chosen to extract the thin sheet with a thickness equal to 2.65 mm, with a height of 170 mm and width of 189 mm, to process the folds and form the U-shape, hoping to obtain the projected dimensions of 100 x 50 x 2.65 mm, as shown in Figure 1.

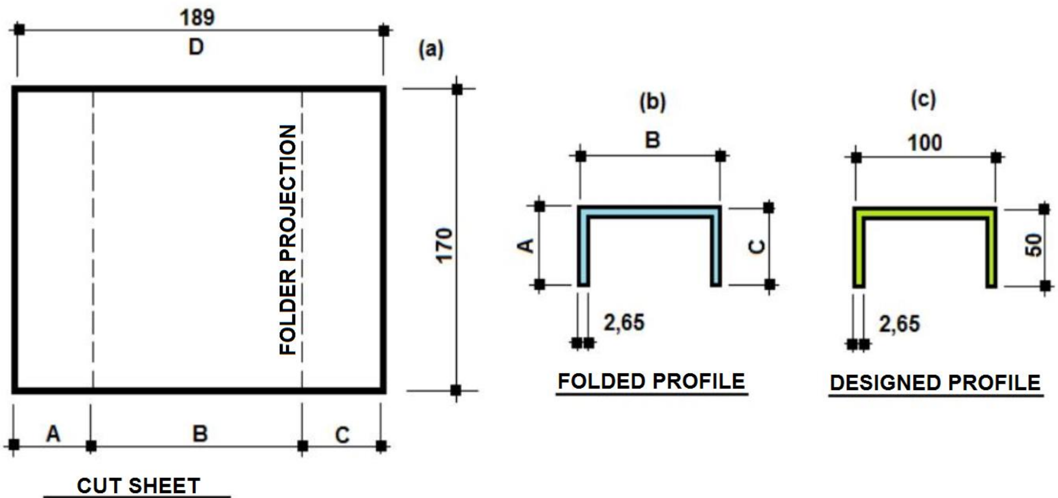


Figure 1 - Preparation of the plate for cold forming, where (a) the plate is ready, (b) processes the profile bent and verified with (c) the profile bent according to the project
(Source: Prepared by the authors)

Through the process of folding the profiles, using a mechanical folder equipped with a cleaver BRAFFEMMAN 1000, 40 samples of this folded profile were produced, as shown in Figure 2.

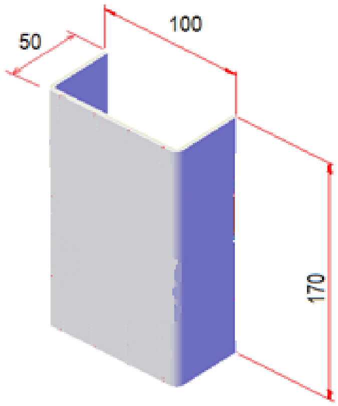


Figure 2 – Folded profile in three-dimensional view
(Source: Prepared by the authors)

2.2 Methods

The dimensions of the folded profile were taken from a TQ1000 digital caliper, based on at least three measurement readings. Volumes were checked using the conventional volumetric displacement technique. Thus, the values were tabulated in an Excel spreadsheet, according to Table 1, containing the geometric characteristics of the samples and expressing their mean values.

Table 1 – Geometric characteristics of the specimen section.

Specimen	Mass	Volume	Dimensions (mm)			
	(g)	(ml)	D	A	B	C
B1-B40	670,34	85,39	189,55	49,41	101,17	49,58

(Source: Prepared by the authors).

Using the AutoCad application, the contour of the sample section was used, through the images collected by a Camera Digital Nikon Coolpix A100, as shown in Figure 3.

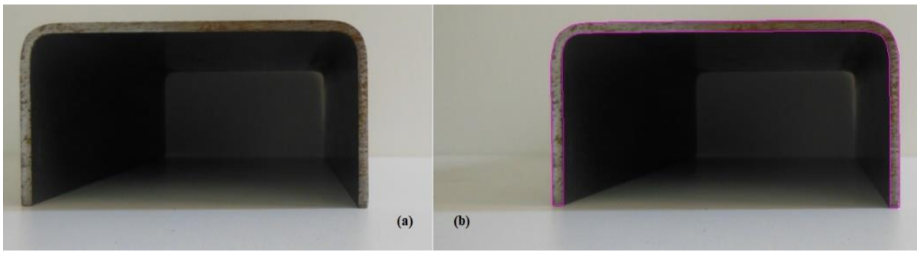
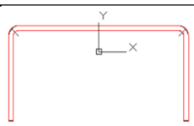


Figure 3 – a) Registered image; b) Contour of the section on the Cad platform
(Source: Prepared by the authors)

With the massprop command, the main geometric properties of each specimen were obtained, which were subsequently statistically evaluated by ANOVA linear regression. And, compared with the projected geometric properties of the profile as shown in Figure 2 and contemplated in Table 2.

Table 2 – Projected geometric properties

Position	Area	Centroide	Moment of inertia		Radius of gyration	
	mm²	y (mm)	x-x (mm4)	y-y (mm4)	x-x (mm)	y-y (mm)
	501,91	37,65	127950	816778	15,97	40,34

(Source: Prepared by the authors)

The evaluation of distortions due to welding was performed using the laser scanning technique, which superimposes images of the joint, before and after welding. For this, a myriad of superficial points were collected throughout the joint, from the images produced by a portable three-dimensional scanner with a rotating base. The data collected in this way allowed superimposing the images of the joints, using the surface analysis computational application Atos Professional V.75S41. With the scans and vector measurements of the extreme points of the sample, randomly selected, one from each sample set, totaled four measurements of test specimens for this process and Figure 4 shows as an illustration the STL file of a welded specimen, copied by scanner.

To improve the reading of the laser beam of the scanned image and avoid reflections in the capture of the cloud of points on the metallic surface of the test specimen, a film of adhesive paste was uniformly applied, the base as a talcum fixer which, when sprayed, formed a homogeneous layer, preserving the material and favoring subsequent cleaning.

Figure 4 - Three-dimensional capture of the laser scanning point cloud

Residual stresses were evaluated by the XRD technique, which is based on the pure graphite matrix with the

equipment properly positioned on the specimen on the reading table, triggers the emission of the X-ray diffraction beam after the protocol preparation that by means of signals sound and visual alerts, Pulstec's U-X360s equipment performs as shown in Figure 5 and to aid in the analysis, the specimens underwent the classic tensile test.

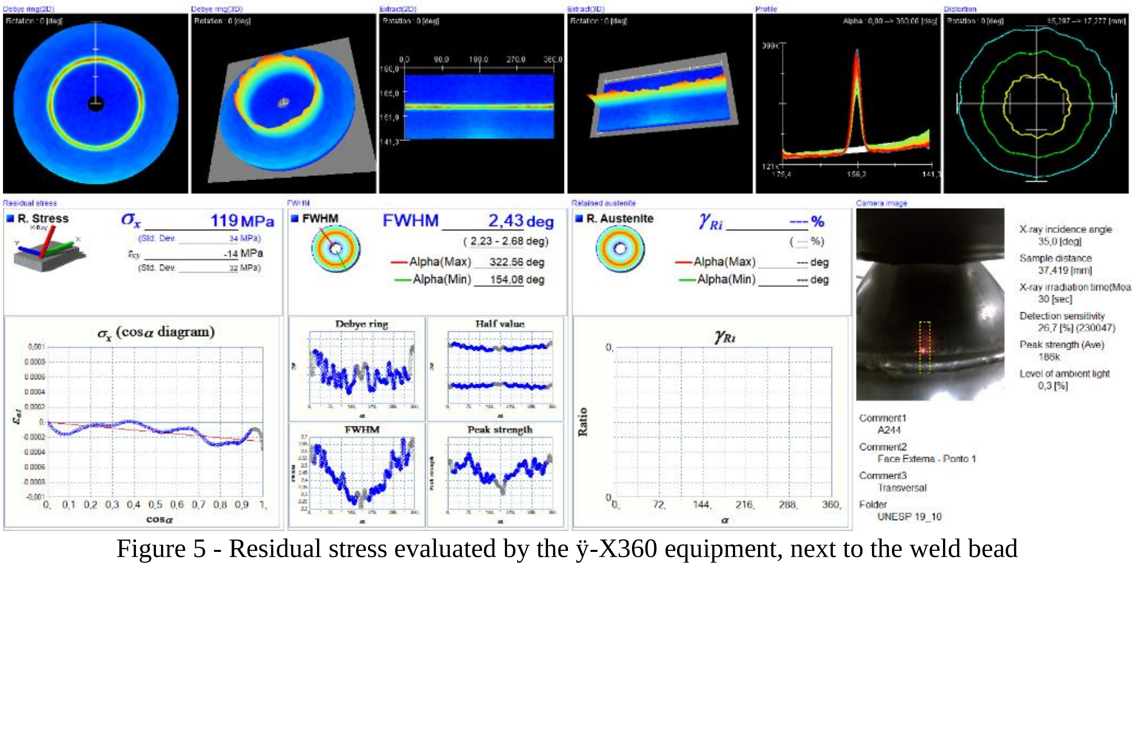


Figure 5 - Residual stress evaluated by the ÿ-X360 equipment, next to the weld bead

The results of residual stresses were in the cutting planes, as shown in Figure 6.

Figure 6 - Representation of the cutting planes in the specimen

2.3 Results and Discussion

As cold-formed profiles are widely used, steel structure factories do not expect the forming process to show a failure in quality control, when the invoice is accompanied by the material certificate. When the real product of the profiles shows inequalities between the same pieces, in their format, it becomes inappropriate when compared with the projected one.

In the reported procedure, the profiles showed distortion and misalignment defects.

Thus, the displacements were isolated, in a vectorial way, fixing the origin of local planes in the section, to identification of one or more defects or even combined ones, according to Figure 7, below.

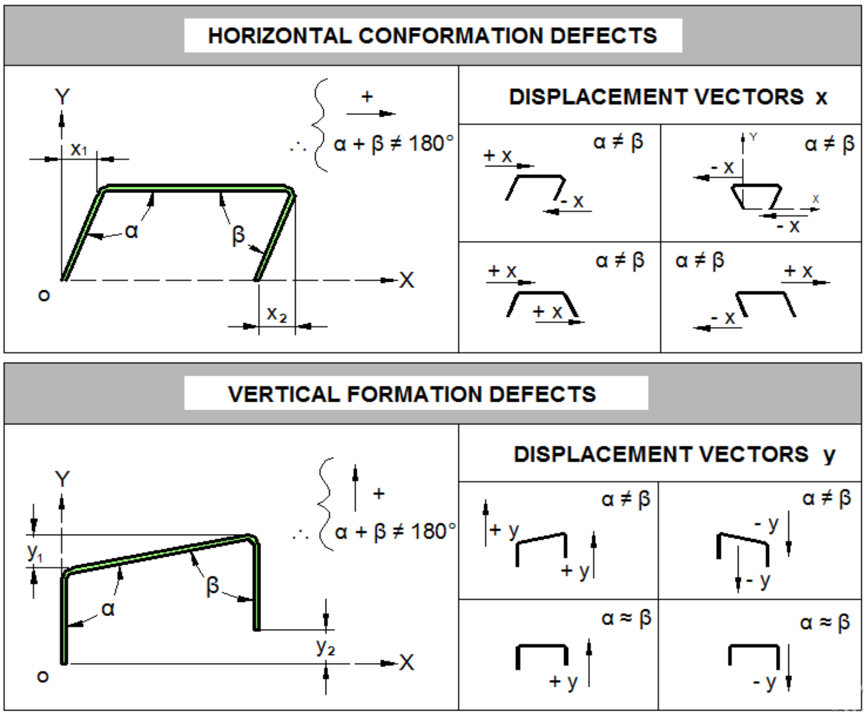


Figure 7 – Local displacements of the bending sheet forming process
(Source: Prepared by the authors)

Observing Table 3, comparing the average values measured with the projected values, the error in the dimensions produced by the conformation process of 1.19% was lower than expected, however, when the cleaver performs the first bend, in the plate, compromises the other folds.

Table 3 – Descriptive statistical analysis

Descriptive statistics	Mass	Volume	Plate cutting	Sequence of folds (mm)		
	g	ml	D (mm)	Tab - A	Soul - B	Tab - C
Projected measurements	669,80	85,32	189,40	50,00	100,00	50,00
Average of samples	670,34	85,39	189,55	49,41	101,17	49,58
Standard error %			0,08	-1,19	1,16	-0,86
Observations	40					

(Source: Prepared by the authors)

Comparing Table 2 with Table 3, it can be seen that significant differences call attention. In general, there are differences in all measurements, modifying the shapes of the cross section of the profile, invisible to perception, raising the problem of materials purchased in the trade to a high degree of heterogeneity, ineffective for standardization. Immediately, focusing on this error only, as it is small for a sample space, the profile would be automatically approved, if there was not a deeper investigation. However, this is aggravated by the final difference of the last fold, with 0.86%, promoting misalignment of the wings and displacement of the center of gravity of the section, which are influential factors in the structural calculation used in the project.

To verify the correlation between the folds, from the flat plate, Student's t test was adopted between the pairs of means and Table 4 indicates that the first folded flap impairs the quality of the profile, with a value of 0.64% , to the detriment of the others, showing that there is a need to review the calibration of the bending equipment, until perfecting the template of the profile to be bent.

Table 4 – Test t: two paired samples for means

Description	D – A	D - B	D - C
Pearson correlation	0,64	0,41	0,35
Gl	39		
Stat t	3661,34	1706,42	2837,05
P(T ≤ t) one-tailed	0	0	0
t one-tailed critical	1,68		
P(T ≤ t) two-tailed	0	0	0
t two-tailed critical	2,02		

(Source: Prepared by the authors)

Discrepancies between the geometric characteristics of the designed profile and those of the samples influence the moment of inertia of the section aggravated by distortion as a result of laser scanning, shown in Figure 8.

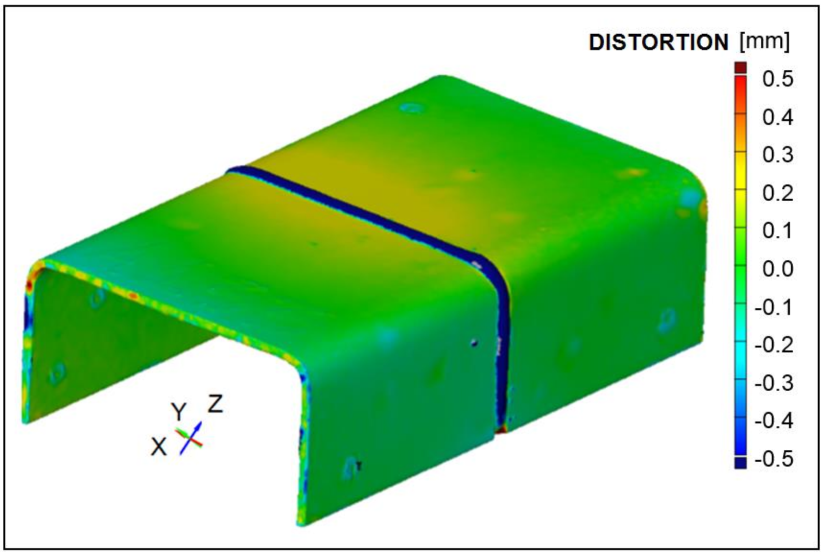
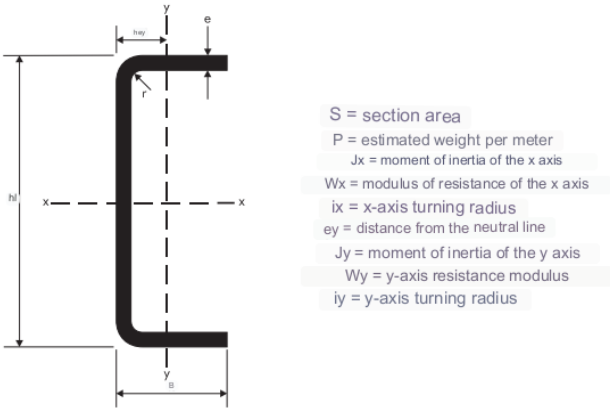


Figure 8 - Distortion in the specimen

The angles between the sides of the profiles are sometimes open angles, sometimes closed angles, enhancing distortion. This modifies, without prediction, the moment of inertia, the center of gravity and other geometric characteristics of the section, used in structural design. Thus, in AutoCad, each section was analyzed, with its due values, and tabulated in Table 5.

Table 5 – Average Moment of Inertia around the x and y axes of the samples



Ix	Iy	Y
mm4	mm4	mm
121412	765164	33,2

(Source: Prepared by the authors)

Comparing the values in Table 2 and Table 5, differences in moments of inertia can be seen with a decrease of 6.3% in the Y direction and 5.1% in the X direction. harmful, if it is considered that the average safety factor used in ABNT NBR 14762:2010 from 1.33 to 1.24. In this sense, structural calculations are compromised when steel yield strengths are used.

Statistical regression for Ix and Iy showed that there is an insignificant relationship with the folds made by the folder, but there may be a variation in width in the cut sheet at the time of cutting, as there is a strong relationship that influences the results. Obtaining a p value of 1.26.10-15 for Iy and 1.18.10-16 for Ix reinforces the possible existence of failure in the cutting of the plates, before the bending process, corroborated by the D values, given in Table 2.

$$Iy = 76931 \cdot D - 13759699$$

$$Ix = 12420 \cdot D - 2223651$$

In order to note the influence of the geometric variation due to the bending process, the metric unit length was assumed and thus compare the U 101.17 x 49.49 x 2.65 mm folded profile and the U 100 x 50 x 2.65 mm design , through the analysis of the average buckling stress to compression and slenderness, obtaining the relationship:

$\lambda x = 62.7$ and ÿxsample = 64.3, impairs buckling around x, 2.6%.

$\lambda y = 24.8$ and ÿysample = 25.6, accentuate the buckling around y with 3.3%.

In bars with low and medium slenderness, variations in buckling stress have little influence on the final result subject to compression force as prescribed in item 9.7 of ABNT NBR 14762:2010.

Therefore, for a better understanding of the problem caused by the bending of the sheet metal, we have the normal compressive strength:

Nc,Rd = 82 kN

Nc,Rd sample = 74 kN

Where Nc,Rd is the profile capacity.

The difference in the resistant values was 10.8% and the highest recorded deviation from the center of gravity was 4.5 mm corresponding to 13.6%, due to defects inserted by the folding process, altering the structural behavior, resulting in first-class eccentricities order.

The results obtained in the field of residual stresses, arising from the action of heat for the melting of metals, show that this amount and intensity directly influence the mechanical phenomena that originate deformations, as close to the weld bead shown in Figure 9.

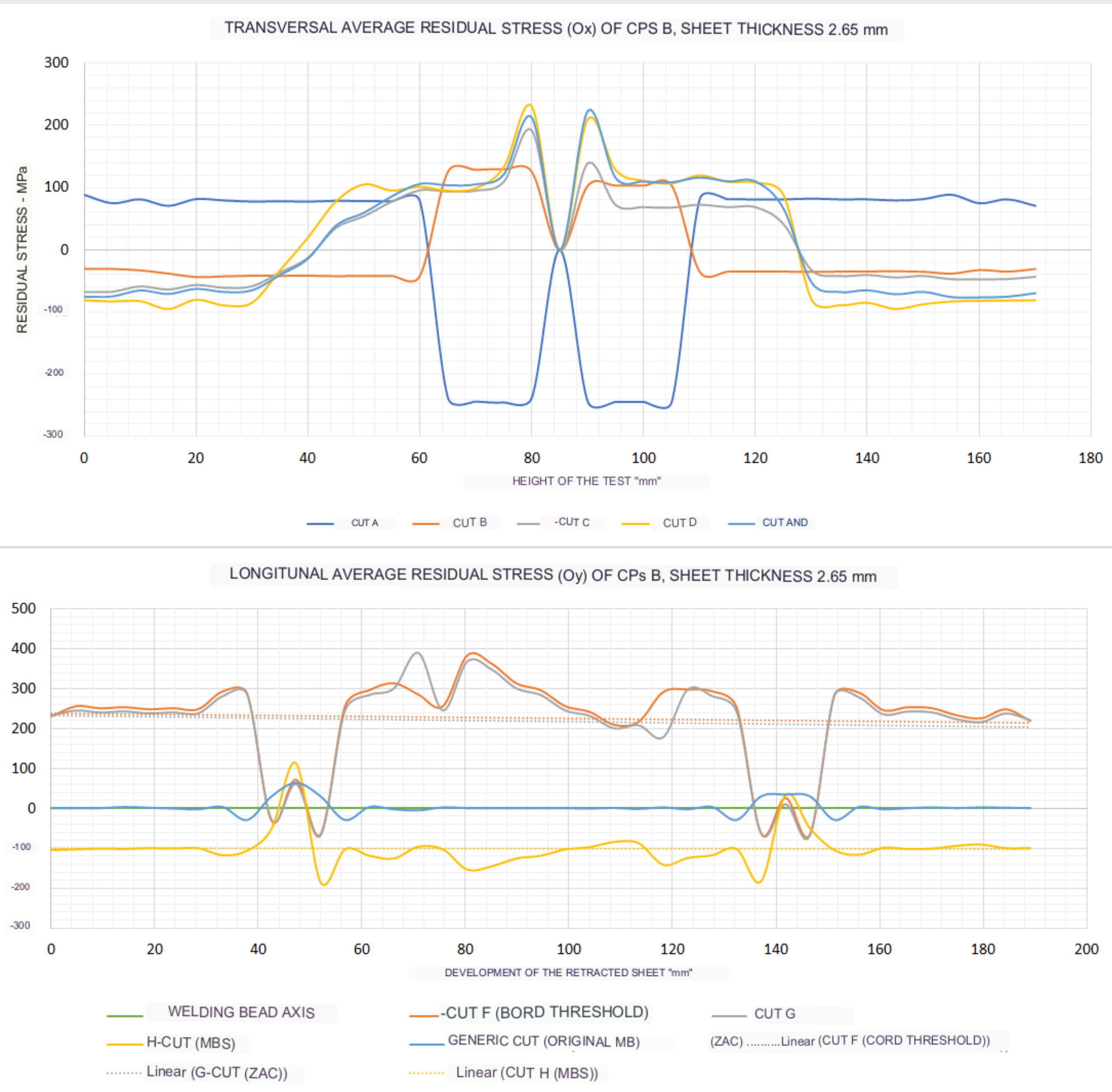


Figure 9 - Graph of average residual stresses ÿx and ÿy for ARBL CSN Civil 300 steels

The stresses by XRD show the incompatible colonization close to the weld, making it possible to have a view of the most critical points regarding the plane stress state, as in the bending region, the tensile stress measured in x 81 MPa and perpendicularly the stress in y compression of 64 MPa plasticizing this region. The tangential stresses in general were always of low values with magnitude below 17 MPa.

The profile region before welding is compromised by a small amount of internal stress due to steelmaking processes, where external forces can act to attenuate or aggravate compression or traction, especially after welding, where residual stress in the region of the weld metal has a record of 295.5 MPa, shown in Figure 9. There was a sufficient microstructural transformation to keep the stress so high without cracking, recording an average of 214.5 MPa with plastification.

The folded region of the structural profile, on the other hand, the effects of residual stresses, presents more critical stresses precisely in the weld metal with values in the order of 296 MPa. Note that the welding heat caused a stress relief in the direction of the y axis, in the order of 24%. On the other hand, crossing these results with those of the tensile test, the fragility formed when there are stress inversions shows that the material acquired a reduction in ductility in the region of the weld bead and an increase in hardness, justifying the tensile test of the test specimen when the heat affected zone breaks outside the posterior weld, shown in Figure 10, always at a distance of 7 mm.

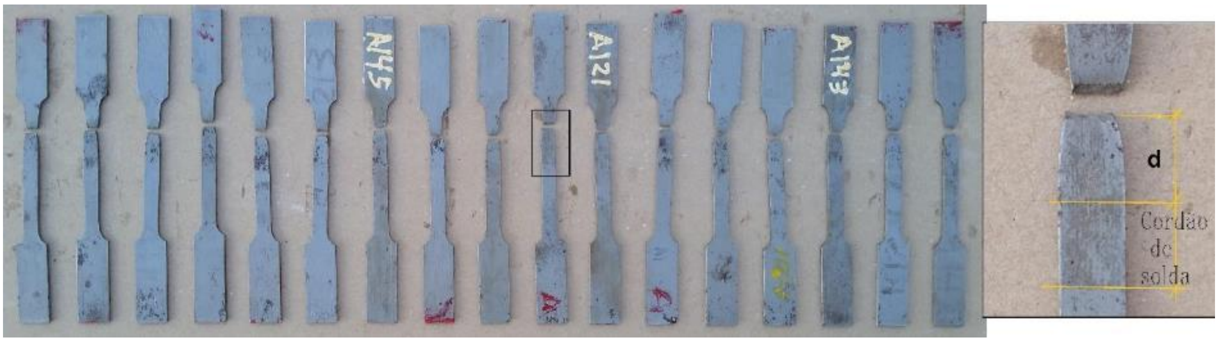


Figure 10 - Breakage of specimens in the tensile test weld

3. CONCLUSION

The bent profile is directly influenced by welding distortions with specific displacements below 450 µm, presenting itself as viable in its practicality and evaluation and ready to be used in robotic systems, perfectly adaptable in factories of metallic structures.

The profile bent in steel CSN-CIVIL-300, despite the geometric similarity with the designed one, presented inequalities after being deformed due to the welding process, which are detrimental to the structural design.

Bending stiffens the sheet by resisting distortions and due to a certain stability of residual stresses finally defined.

The bending defects in the profile caused a deficit in the normal compressive strength above 10.8%, considering the aggravation of the welding distortions.

The "U" type cold formed structural profile requires care and recommendation for periodic inspection in the welded joints subject to requests with magnitudes that extrapolate the elastic phase of the material.

The behavior of the "U" type bent profile is very sensitive to the action of welding, due to the distortions that cause harmful deformities, mainly in the structural calculation of the project.

4. ACKNOWLEDGMENTS

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5. REFERENCES

AMARAL, M. (2022). *Análise teórica e experimental de um sistema de treliças padronizadas em perfis de aço formados a frio* (2022 ed., Vol. I). São Carlos, SP, BR: UFSCAR. doi:doi:10.11606/D.18.2022.tde-22022022-090846.

ASSOCIAÇÃO BRASILEIRA DE NORMAS TÉCNICAS. NBR 6355: Perfis estruturais de aço formados a frio — *Padronização.* Rio de Janeiro, p. 36, 2012.

ANTUNES, P. D. Influência do metal de adição na susceptibilidade à corrosão sob tensão de juntas soldadas do aço inoxidável ferrítico AISI 444 em meios contendo cloreto de magnésio. 2010. 124 f. *Dissertação (Mestrado em Ciências dos Materiais para Engenharia)* – Universidade Federal de Itajubá, Itajubá, 2010.

BORGES, V. M.; LINS, J. F. C. Estudo da Influência do Boro no Aço 10B45 (Fio-máquina e Arame Trefilado), analisando propriedades mecânicas e microestruturas. *Cadernos UniFOA*, Volta Redonda, n. 36, p. 5-14, abr. 2018.

CORDEIRO, S. G. F. Contribuições às análises de fratura e fadiga de componentes tridimensionais pelo Método dos Elementos de Contorno Dual. 2018. *Tese (Doutorado em Estruturas)* – Escola de Engenharia de São Carlos, São Carlos, 2018.

PEREIRA, J. P. (15 de ABRIL de 2020). Variação das propriedades geométricas do perfil estrutural dobrado tipo U e influencia no projeto de estrutura metálica. *REA, I(2020), 10*. Acesso em 17 de SETEMBRO de 2022.

PEREIRA, S. A. A. Inspeção de obras de arte metálicas e mistas - Caso de estudo: Ponte de D. Luís sobre o rio Tejo. 2018. 83 f. *Dissertação (Mestrado em Engenharia Civil)* – Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa, Lisboa, 2018.

RIBEIRO, J. C. R. S. Análise de tensões residuais e deformações em soldadura. 2010. 71 f. *Dissertação (Mestrado em Engenharia da Soldadura)* – Universidade Nova de Lisboa, Lisboa, 2010.

SACCHI, C. C. Avaliação de desempenho estrutural e manifestações patológicas em estruturas metálicas. 2016. 137 f. *Dissertação (Mestrado)* – Universidade Federal de São Carlos, São Carlos, 2016.

SOARES, H. C. G. Estudo de sequência de soldagem para redução e eliminação de distorções. 2006. 95 f. *Dissertação (Mestrado em Engenharia Mecânica)* – Universidade Federal de Minas, Belo Horizonte, 2006.

VERGILIO, S. A. L. Ligações em estruturas metálicas com ênfase em perfis formados a frio. 2011. 157 f. *Dissertação (Mestrado em Engenharia Civil)* – Faculdade de Engenharia de Ilha Solteira da Universidade Estadual Paulista "Júlio de Mesquita Filho", Ilha Solteira, 2011.

6. RESPONSIBILITY FOR INFORMATION

The authors are solely responsible for the information included in this work.

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