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Experimental Investigation of the Mechanical Properties of ZAR-345 Cold-Formed Steel at Elevated Temperatures

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Considering the technical-scientific advances of recent years in the steel construction industry, there is a strong trend for the increasing use of cold-formed steel members in civil construction, due to several advantages such as cost and versatility of fabrication and erection. However, there is need for further study concerning the behavior of this type of steel when subjected to fire conditions. This work deals with the experimental characterization of cold-formed steel at high temperatures. It is recognized that the reduction factors of the mechanical properties applicable to hot-rolled steel members do not remain valid for cold-formed ones. In the case of the European Code, cold-formed members are treated in the same way of hot-rolled or welded thin-walled sections (*i.e.*, class 4), the only differences in relation to the other (class 1, 2 or 3) consisting (i) the definition of the yield strength and (ii) the corresponding reduction factors (shown in Table E.1 of appendix E of EC3-1.2:2005). In this context, coupon tensile tests were carried out according to recommendations proposed by AS 2291:2007 standard for ZAR-345 (ABNT NBR 7008-1:2012) (or ASTM A653-2011- SS50(340)C1, equivalent). The variation of the constitutive relations (stress-strain-temperature curves) was measured for different uniform temperatures, ranging from 20 °C (ambient) to 100-200-300-400-500-600 °C. The obtained experimental results indicate a clear distinction with the models proposed by other authors as well as specifications of EC3-1.2:2005.

Keywords: *Cold-Formed Steel, elevated temperatures, experimental investigation, mechanical properties, stress-strain curves, ZAR-345 ABNT NBR 7008-1:2012 steel, ASTM A653-2011 - SS50(340) C1 steel*

1. Introduction

The use of lightweight steel structures in building construction began in the United States and England around the year 1850, but was still limited to small residential buildings. During and after the Second World War, the steel industry began to develop on a larger scale, enabling the evolution in manufacturing processes of cold-formed steel.

Since the mid-1930s, there were standards for the design of steel structures considering hot-rolled steel members. Realizing the necessity of a normative procedure for the design of cold-formed steel structures, the *American Iron and Steel Institute* (AISI) initiated a specific study. Thus, in 1946, it was published the first edition of the AISI, *Specification for the Design of Light Gage Steel Structural Members*. Later, with the development of new studies in this area, other versions of the standard AISI were published and the most recent is named *North American Specification for the Design of Cold-Formed Steel Structural Members* (AISI - S100, 2007)[1].

From the year 1960, the structures of thin steel plate had new and different applications, such as walls involving stairway towers of buildings and elevator wells constructed without the use of scaffoldings. Since then, the use of cold-formed steel is increasing in the construction of industrial, residential and commercial buildings, as shown for example in Figure 1.

Figure 1. Building construction in Lightweight Steel Framing system[2].

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In parallel to this trend, the need to analyze the resistance of cold-formed steel structures when exposed to the fire action is very important for the implementation of a safe and economical design.

1.1. *Motivation*

The definition of the mechanical properties is essential for the design of steel structures, because these can be strongly affected in cases of fire, resulting in loss of strength and stiffness. The early researches related to steel structures submitted to fire situation dealt exclusively with hot-rolled steel. The most relevant standards, such as ABNT NBR 14323:2003[3], recommend reduction factors for mechanical properties of hot-rolled steel. However, such reduction factors are considered inappropriate for cold-formed steel.

Some authors have developed experimental research with samples of cold-formed steel to: (i) evaluate the behavior of this type of steel at elevated temperatures, (ii) propose representative analytical models and (iii) obtain values for the reduction factors of the mechanical properties. However, there are significant differences between results obtained in different studies for these reduction factors. In addition, the values recommended by standards such as EC3-1.2:2005[4], which differentiates the cold-formed from the hot-rolled steels when it comes to the reduction factors, are also divergent with respect to the results of existing researches.

1.2. *Objective and scope of the paper*

In this context, this study aims to develop experimental analysis to determine the constitutive relation of cold-formed steel ZAR-345[5] (or ASTM A653-2011-SS50 (340) C1 equivalent)[6], submitted to high temperatures (uniforms). As part of the objectives, the following were also achieved: (i) the values of the reduction factors of mechanical properties in accordance with the results obtained directly from the experimental investigations, (ii) evaluation of the behavior of stress-strain-temperature curves, (iii) proposition of analytical models for the constitutive relations of the cold-formed steel, depending on the temperature adopted, and (iv) comparison of the results with available researches and current standards.

In section 2, the experimental methodology used in the tests of this study is described. Initially, the equipment and the specimens used in experimental investigations are presented. Subsequently, the assembly sequence established for the preparation of the mechanical tests at high temperatures is explained and, finally, the whole experimental procedure is detailed as well as the steps of calibration and acquisition of the experimental data.

The results of the experimental investigations are given in section 3. Besides the evaluation of the specimens after the end of the tests, this section involves the stress-strain curves according to the temperature considered, obtaining the mechanical properties, such as yield strength and elastic modulus, in each temperature and calculating the corresponding reduction factors. At the end of the results, comparisons with the reduction factors values obtained by other researchers and by EC3-1.2:2005[4] are performed and an analytical model to represent the behavior of the stress-strain curves of cold-formed steel for each temperature is proposed, taking into account the experimental analyzes performed in this work.

Finally, in section 4, some final remarks and suggestions for future work are presented.

2. Experimental Procedure

In this study, the mechanical stress-deformation properties of light gauge cold-formed ABNT NBR 7008-1:2012[5] ZAR-345 steel (equivalent to ASTM A653-2011-SS50(340)C1)[6] at elevated temperatures is determined by the steady-state test method. Due to its simplicity and accurate data acquisition, many other researchers have also used the steady-state test method[7-10]. Outinen[7] and Lee et al.[9] carried out both steady-state and transient-state tests of cold-formed steels and showed that the difference between steady-state and transient-state test results was negligible.

2.1. *Testing specimen*

Coupon tensile test specimens were taken in the longitudinal direction of the virgin thin plate coil with plate thickness of 2.7 mm, from the cold-formed ZAR-345, with nominal yield strength (0.2% proof stress) of 345 MPa at normal room temperature. The specimens dimensions were decided based on AS 2291:2007 standard[11], as illustrated by Figure 2. The chemical compositions of the test specimens are presented in Table 1. A single hole was provided at each end of the specimen in order to fix them, with M10 bolts, to the loading shafts located at the top and bottom ends of the

Table 1. Measured chemical properties of steel specimens.

C(%)	Mn(%)	P(%)	S(%)	Al(%)
0.18	0.75	0.016	0.007	0.044

Note: Percentage of element by weight.

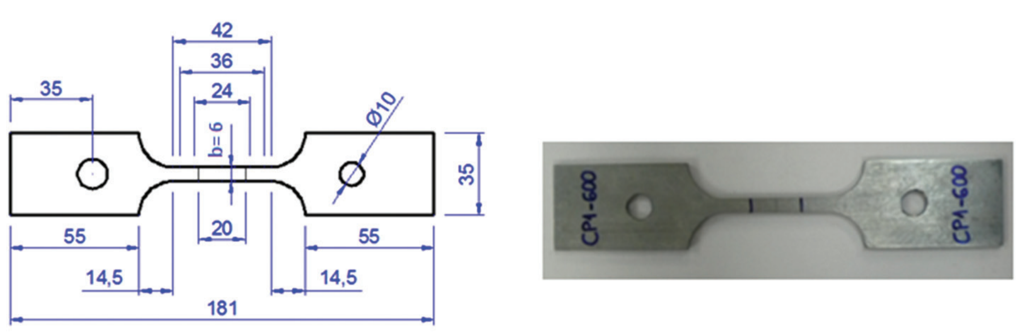

Figure 2. Dimensions of the tensile test specimens (mm).

furnace. The fastening system of the samples was composed at each end by two plates with thickness of 5 mm, a bolt of 10 mm diameter with hexagon nut, a pin of 12.5 mm diameter and two washers with external diameter of 20 mm, all made of stainless steel. The dimensions of the specimen ends and the holes were designed to avoid any premature failure at the holes. A total of 13 tests were conducted in this study. The specimen's metal thickness and width were measured using a micrometer and a venire caliper, respectively. The averages of these measured dimensions were used in the calculations of the mechanical properties.

2.2. *Testing device*

A *Shimadzu Servopulser Universal* testing machine of 300 kN capacity was used in this study, as shown in Figure 3a, which was calibrated before testing. Figure 3b illustrates the high temperature furnace, with a maximum temperature of 1000 °C. The furnace temperature was controlled by a *Shimadzu servopulser* temperature controller. The installation of the coupon specimen and the testing device used are shown in Figure 3c. The measuring equipment included LVDT and force transducers mounted with a loading machine, and an EHF-EM300K1-0700A *shimadzu* high temperature clip-gauge with a maximum working temperature of 1200 °C and a gauge length of 20 mm, given by Figure 3d. A total of two pairs of type-K thermocouples, connected to a Kyowa temperature meter, were located inside the furnace to measure: the air temperature and the surface temperature of the specimen, which was assumed to be the actual temperature of the specimen in the current work. The location of thermocouples on the samples surface was according to specifications provided by AS 2291:2007[11], as illustrated by Figures 3e to 3f.

The differences between the temperatures detected by the internal and external thermal couples were ranged from 3% to 28%. The temperature accuracy of the internal and the external thermal couples was 1.0 and 70.1 °C. The heating rate of the furnace is 100 °C/min. The fast heating rate resulted of the temperatures overshoot slightly, but the overshoot stabilizes within a minute. The maximum overshoot was approximately 40 °C at low temperatures and decreases at higher temperatures. When the temperature beyond 700 °C, the overshoot was less than 20 °C. An MTS Model 632.53F-11 of axial extensometer was used to measure the strain of the middle part of the coupon specimen. Gauge length of the extensometer was 25 mm with range limitation of 72.5 mm. The extensometer was also calibrated before testing. The extensometer was reset when it approaches the range limit during testing, hence a complete strain of coupon specimen can be obtained.

Before loading, a level laser device was used to check the frontal and lateral alignment of the samples in relation to the fastening system, thus ensuring the centered application of tensile force.

A hydraulic actuator was used to apply the tensile load to the specimens with the help of MultiPurpose TestWare (MTS) system. A load cell connected to the top loading rod was used to measure the tensile load. Alignment of the test set-up is one of the most important factors, and hence it was always checked by applying a pre-tensile load of 200 N to the specimen. The top and bottom rods were first aligned vertically with each other, and then the specimen alignment with these rods was ensured.

2.3. *Testing procedure*

First of all, the calibration of the clip-gage was performed with the aid of the *Shimadzu* device calibrator CDE-25. Fixing the rods of the clip-gage at the calibrator device, it was possible to control the exact displacement and obtain data from both devices simultaneously.

In addition, a simples tensile test was conducted at room temperature using two types of extensometer, the clip-gage and a strain-gage, to obtain both deformation data during the test. The results proved the validity of the values measured by the clip gage.

In the current steady state tests procedure, the specimen was heated up to a specified temperature, T = 20-100-200-300-400-500-600 °C, then loaded until it failed while maintaining the same temperature. In the present study, thermal elongation of specimen was allowed by maintaining zero tensile loads during the heating process.

After reaching the pre-selected temperature, by means of a chosen heating rate of approximately 10 ºC/min, the specimen needs less than 3 min for the temperature to stabilize. Moreover, it needs another 15 min (as specified by AS 2291:2007)[11] to allow the heat to transfer into the specimen, then the tensile load applied to the specimen. Two externals thermocouples indicated that the variation of the specimen temperature within the gauge length was less than ±3 °C during the tests, as shown in Figure 4. It indicates that there was an adequate control of the temperature variations of the samples.

A constant tensile loading rate of 0.004 mm/s was used and the strain rate obtained from the extensometer was approximately 0.0002 s^{-1}, which is within the range 0.0002 s^{-1} and 0.0008 s^{-1} as specified by the AS 2291:2007[11].

The application of the tensile loading was taken in order to deform the specimens steadily without decreasing load and without any shock or vibration in the test system. Due to careful centering, as described before, the force was accurately applied along the axis of the specimen to minimize the effects of bending and torsion. Thus, the test continued until the fracture of the samples.

During the mechanical test, the S*himadzu servopulser* provides data like tensile force applied to the specimens and displacements measured by the clip-gage. These output data were automatically recorded with an acquisition frequency of 2 Hz.

The stress-strain curves were obtained by dividing the values of tensile force by the values of area sections (thickness and width measured) and the values of displacement by the value of the gauge length (20 mm), corresponding to each temperature considered in the tests.

3. Results and Discussion

3.1. *Behavior of the samples after testing*

During the experimental tests, it was observed that the samples lose a portion of ductility when subjected to temperatures up to 200 °C. This was verified by the elapsed

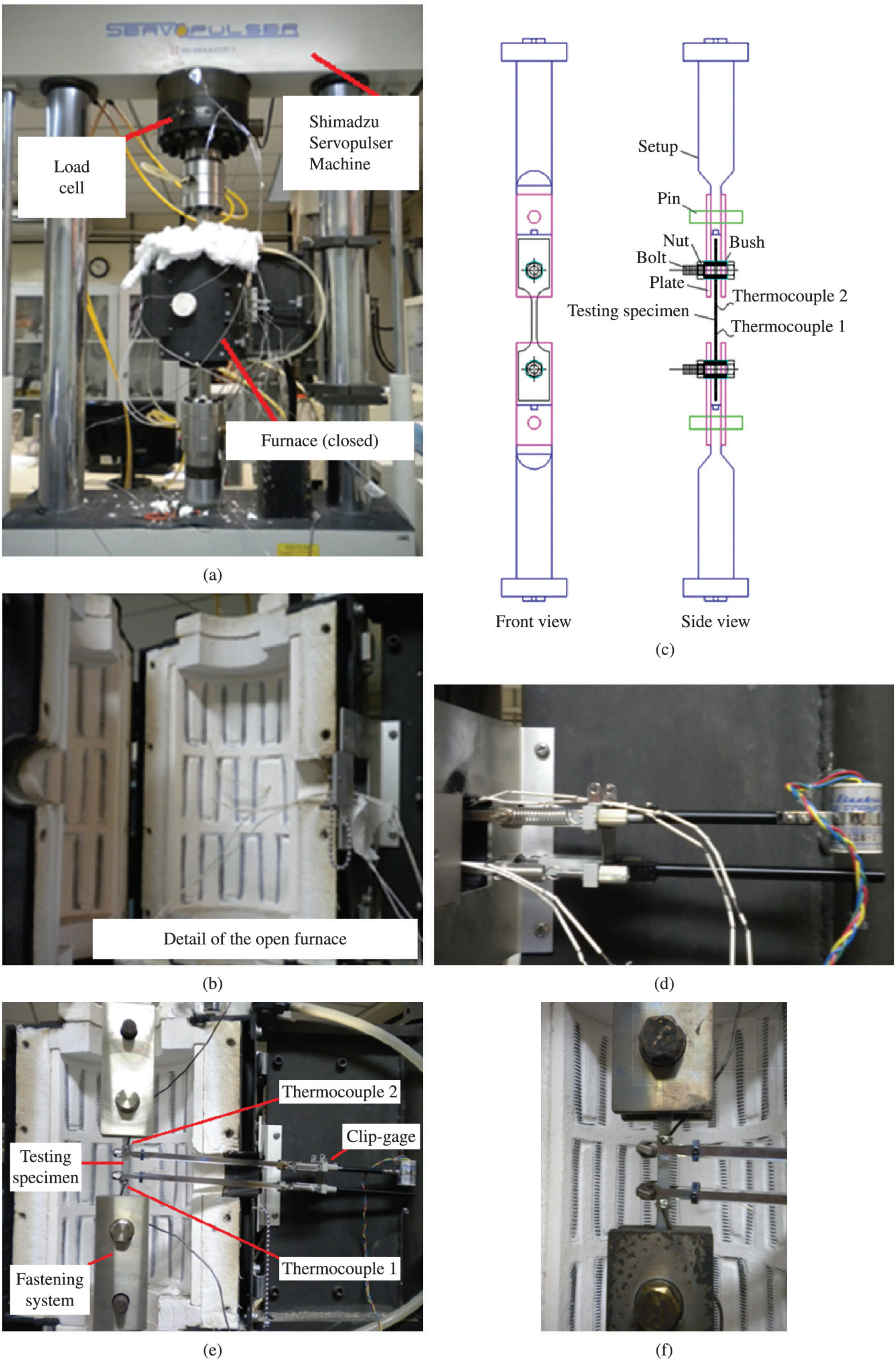

Figure 3. Details of test arrangement.

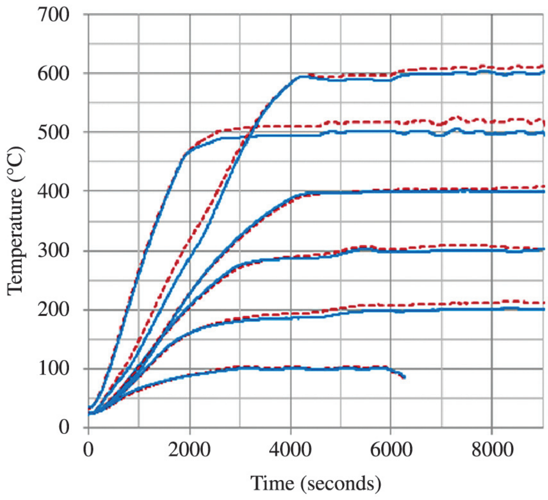

Figure 4. Temperature variations of the specimens as a function of time in seconds.

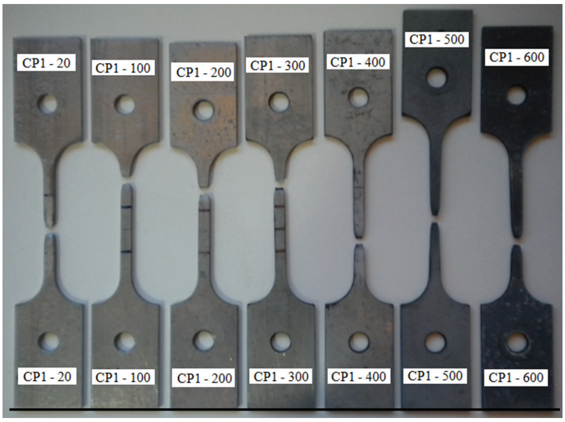

Figure 5. Typical failure modes during steady state tests.

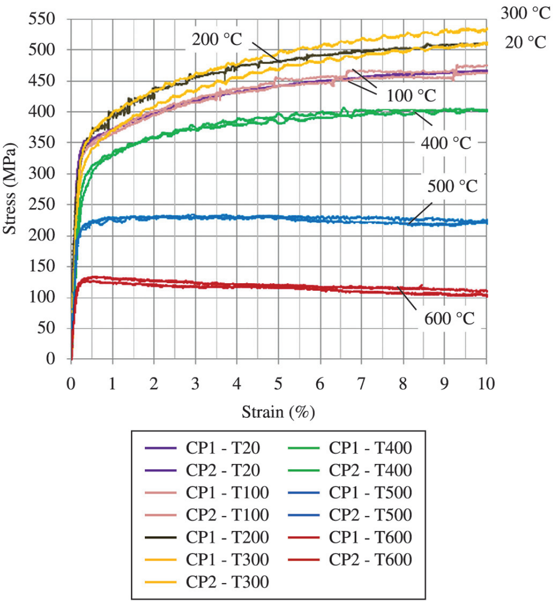

Figure 6. Stress-strain-temperature curves, with deformation ranging from 0 to 10%.

time in the tensile test until failure and by the final stage of the specimen's central part visual examination. The time of the tensile test at room temperature was approximately one hour, while in cases of 100 °C and 200 °C , this time reduced to approximately 30-40 minutes. The same effect was also noted by Kankanamge and Mahendran[12], who observed a loss of 50% in ductility at the tests considering 100 °C in relation to tests with 20 °C. Wei and Jihong[13] and Ranawaka and Mahendran[8] obtained a similar behavior in their trials and argue that this effect occurs because of the chemical reactions that act in cold-formed steel due to its small nitrogen content, when subjected to this temperature range. The strength of the steel may increase due to the occurrence of these chemical transformations. On the other hand, with the increase of temperature to values above 200 °C, the same reactions are delayed and, as a result, the ductility increases. In tests with samples subjected to temperatures of 300 °C and 400 °C, the elapsed time during the tensile test was approximately 50-55 minutes, showing a recovery of ductility. And the tests considering 500 °C and 600 °C lasted between one hour and one hour and a half until the specimen's failure, indicating a greater ductility. At this stage, despite the tests were performed in a reasonable reduced time – indeed, one recognizes that creep effects were also included in the performed tests. Another factor that proves this effect is a visible difference in the final stages of samples corresponding to temperatures of 500 °C and 600 °C, as shown in Figure 5. It can be observed that the testing specimens deformed more, before failure, in the tests subjected to higher temperatures.

3.2. *Obtaining the stress-strain curves for each temperature*

With the values of stress and strain obtained in each experimental test, curves of the constitutive relations were plotted according to each temperature value (20-100-200-300-400-500-600 °C, respectively), as shown in Figure 6.

The stress-strain-temperature curves show a small variation between the results obtained for the case of room temperature and 100 °C, so that the stress values measured are very close in the four tests (CP1 and CP2 at 20 °C, and CP1 and CP2 at 100 °C). The transition between the elastic zone and the yield point is similar considering the experiments performed at 20 °C and 100 °C and the experiments performed at 200 °C and 300 °C. However, in the tests adopting 200 °C and 300 °C, there is a significant increase (approximately 11%) of the stress values measured (more pronounced hardening effect). On the other hand, in the case of stress-strain curves plotted for the temperature of 400 °C, it is observed that the stress values suffered a considerable reduction compared with previous cases of lower temperatures. Subsequently, it is possible to notice the loss of resistance and stiffness as the temperature increases. The tests performed at the temperature of 500 °C showed an even greater reduction of the stress values and the yield zones. Finally, the test results corresponding to 600 °C also indicated that the stress values are considerably smaller than the case of 500 °C and, in addition, assume a decreasing rate as the deformation increases (softening effect).

3.3. *Yield strength and elastic modulus reduction factors*

With the stress-strain curves, it was possible to obtain the values of yield strength (corresponding to the residual strain of 0.2%) and elastic modulus (slope of the initial portion of the stress-strain curve) for each temperature considered. Thus, the reduction factors of mechanical properties were calculated according to each case of temperature (two testing specimens per temperature) and the values are presented in Table 2. Figures 7a and 7b show the reduction factor points and the average curve for K_y (reduction factors of yield strength) and K_E (reduction factors of elastic modulus).

3.4. *Comparison of yield strength and elastic modulus reduction factors with available research results*

Figures 8a and 8b present the variation of the reduction factors according to the models adopted by researchers, the EC3-1.2:2005[4] and the experimental data obtained in the tests.

The resume graphic shows that the average variation of reduction factors (K_y and K_E) obtained in the tests differs from other curves presented, depending on the temperature.

Considering K_y, in the range of 20 °C and 100 °C, the behavior of all the curves are similar, whereas there is no significant difference in loss of steel resistance. In case of 200 °C, there is an increase of yield strength, which was not noted in other researches, and at 300 °C, this value is close to that recorded in case of room temperature. In the range of 350 °C and 600 °C, the results of the tests are shown substantially similar to the model used by Chen and Young[14]. Otherwise the curves adopted by Kankanamge and Mahendran[12] and Wei and Jihong[13] presented lower values. Reduction factors (K_y) recommended by EC3-1.2:2005[4], for hot-rolled steel, are above the average curve obtained considering temperatures above 300 °C, proving the divergence between the changes of mechanical properties of hot-rolled and cold-formed steels. Moreover, the reductions defined by EC3 -1.2:2005[4] to cold-formed steel are underestimated for all the temperatures (20 °C to 600 °C).

Considering K_E, in case of 100 °C, there was a very marked reduction in elastic modulus compared with the models adopted by the other researchers. In the temperature range of 200 °C and 300 °C, the variation of the reduction factors obtained from tests approaches curves adopted by Chen and Young[14], Kankanamge and Mahendran[12] and Lee et al.[9]. In the range of 300 °C and 450 °C, there is a similarity between the K_E factors obtained and those presented by Chen and Young[14] and, finally, from 450 °C to 600 °C, the test results are close to the values determined by Wei and Jihong[13]. Reduction factors (K_E) recommended

Table 2. Reduction factors according temperature.

Temperature (°C)	$f_{y,T}$ (MPa) CP1	CP2	K_y CP1	CP2	E_T (GPa) CP1	CP2	K_E CP1	CP2
20	345	352	1.000	1.020	200	211	1.000	1.056
100	342	344	0.991	0.997	175	157	0.875	0.785
200	359	-	1.041	-	162	-	0.810	-
300	359	330	1.041	0.957	145	157	0.725	0.785
400	291	305	0.843	0.884	125	137	0.625	0.685
500	214	219	0.620	0.635	115	123	0.577	0.615
600	130	125	0.377	0.362	70	67	0.350	0.333

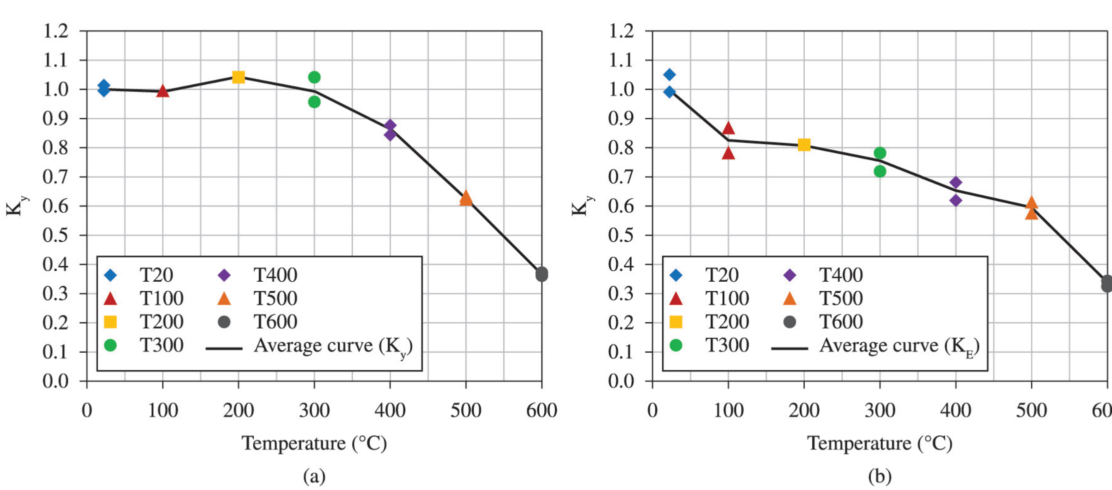

Figure 7. Reduction factors points for each specimen according temperature and average curves: (a) yield strength K_y and (b) elastic modulus K_E.

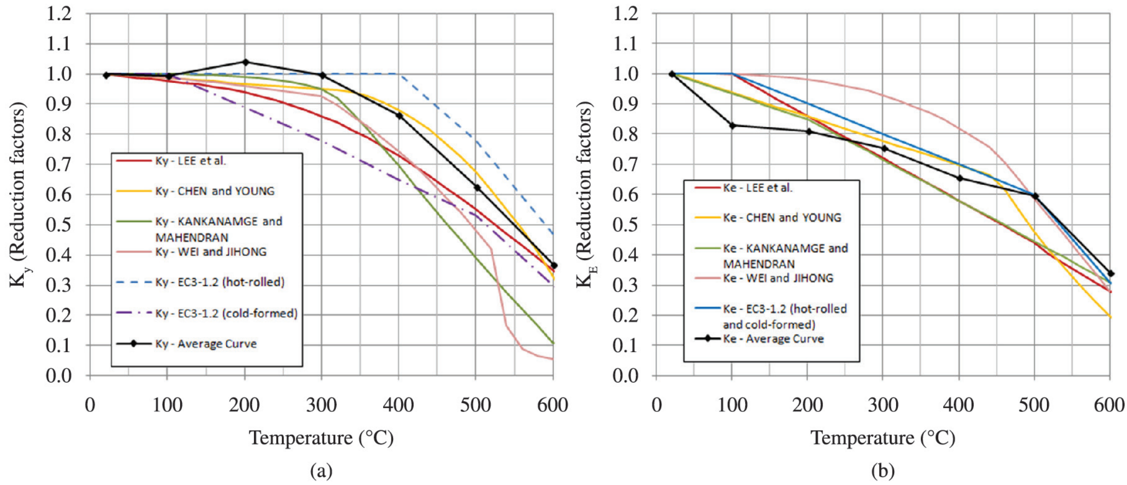

Figure 8. Reduction factors according with temperature variation: (a) yield strength K_y and (b) elastic modulus K_E.

by EC3-1.2:2005[4] are overestimated when compared to the values obtained in the tests until the temperature of 500 °C.

3.5. *Proposed stress-strain curve model*

Given the differences between the selected researches for the determination of stress-strain-temperature curves, a new model is proposed in order to represent the behavior of these constitutive relations based on the results obtained experimentally.

The proposed model stress-strain curve was based on Ramberg and Osgood[15] equation for elevated temperatures, as shown in Equation 1, considering $f_{y,T} = K_y f_{y,20}$; $E_T = K_E E_{20}$; $f_{y,20}$ = 345 MPa ; E_{20} = 200 GPa ; and β = 0.86. The expressions for K_y e K_E are defined in Equations 2 and 3 and the parameter n is defined in Equation 4.

$$\varepsilon_T = \frac{f_T}{E_T} + \beta\left(\frac{f_{y,T}}{E_T}\right)\left(\frac{f_T}{f_{y,T}}\right)^n \quad (1)$$

$$K_y = \begin{cases} 1 & for\, 20\,°C \le T < 300\,°C \\ 2x10^{-9}\,T^3 - 6x10^{-6}\,T^2 + 0.0019\,T + 0.916 & for\, 300\,°C \le T \le 600\,°C \end{cases} \quad (2)$$

$$K_E = \begin{cases} -0.0009\,T + 1.018 & for\, 20\,°C \le T < 500\,°C \\ -0.002\,T + 1.568 & for\, 500\,°C \le T \le 600\,°C \end{cases} \quad (3)$$

$$n = \begin{cases} -1x10^{-8}\,T^4 + 9.061x10^{-6}\,T^3 - 0.002588085\,T^2 + 0.210559733\,T + 14.753 \\ \qquad for\, 20\,°C \le T < 400\,°C \\ -0.000925\,T^2 + 1.1675\,T - 307.5 \qquad for\, 400\,°C \le T \le 600\,°C \end{cases} \quad (4)$$

Figure 9 shows the stress-strain-temperature curves according to the proposed analytical model and the corresponding experimental curves at different temperatures. There is a good correlation of the experimental data and the analytical model. Therefore, it represents adequately the behavior of ZAR-345 cold-formed steel, tested in this study, at elevated temperatures.

3.6. *Comparison of the proposed stress-strain curve model with other researchers models*

Available and proposed models for stress-strain-temperature curves are presented in Figure 10 in order to enable a better comparison between all the results.

Analyzing the models presented, there is a clear difference between the stress-strain-temperature curves, including the analytical model described in Section 3.5. In the case of temperatures from 20 °C to 400 °C, the proposed model describes curves with stress values systematically higher than those presented by other researchers and the EC3-1.2:2005[4]. Especially in the range of 200 °C and 300 °C, stress values are even higher, as already detected earlier, showing a more pronounced increase of resistance. Considering the case of 200 °C, the difference between the maximum stress value obtained for a strain of 10% and the maximum stress value according Wei and Jihong[13] is approximately 90 MPa. In the case of 300 °C, this difference compared to Chen and Young[13], Kankanamge and Mahendran[12] and Wei and Jihong[13] models is equivalent to 100 MPa. At temperatures of 20 °C and 100 °C, the difference between the maximum stress values obtained

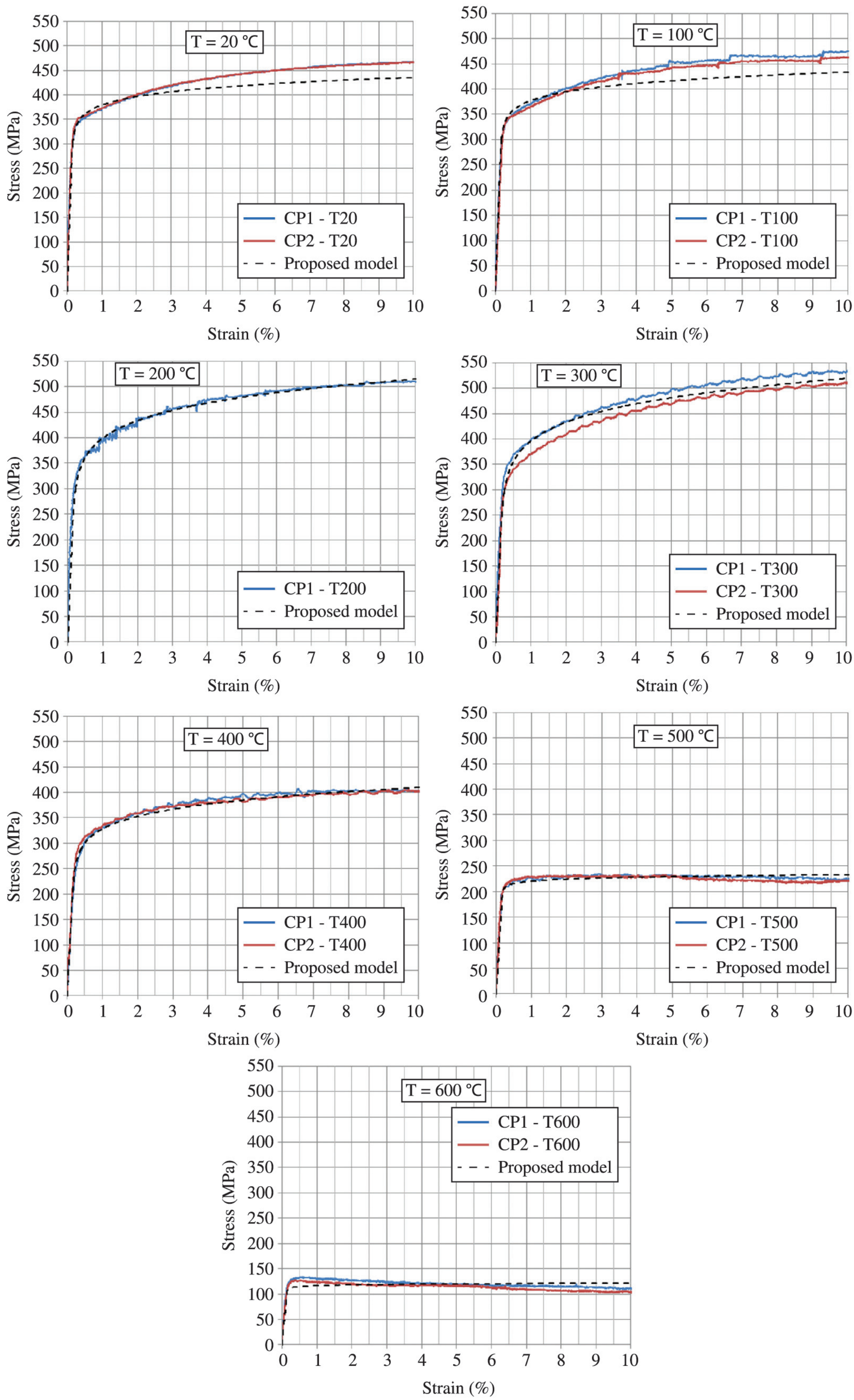

Figure 9. Stress-strain curves for each temperature, according proposed model.

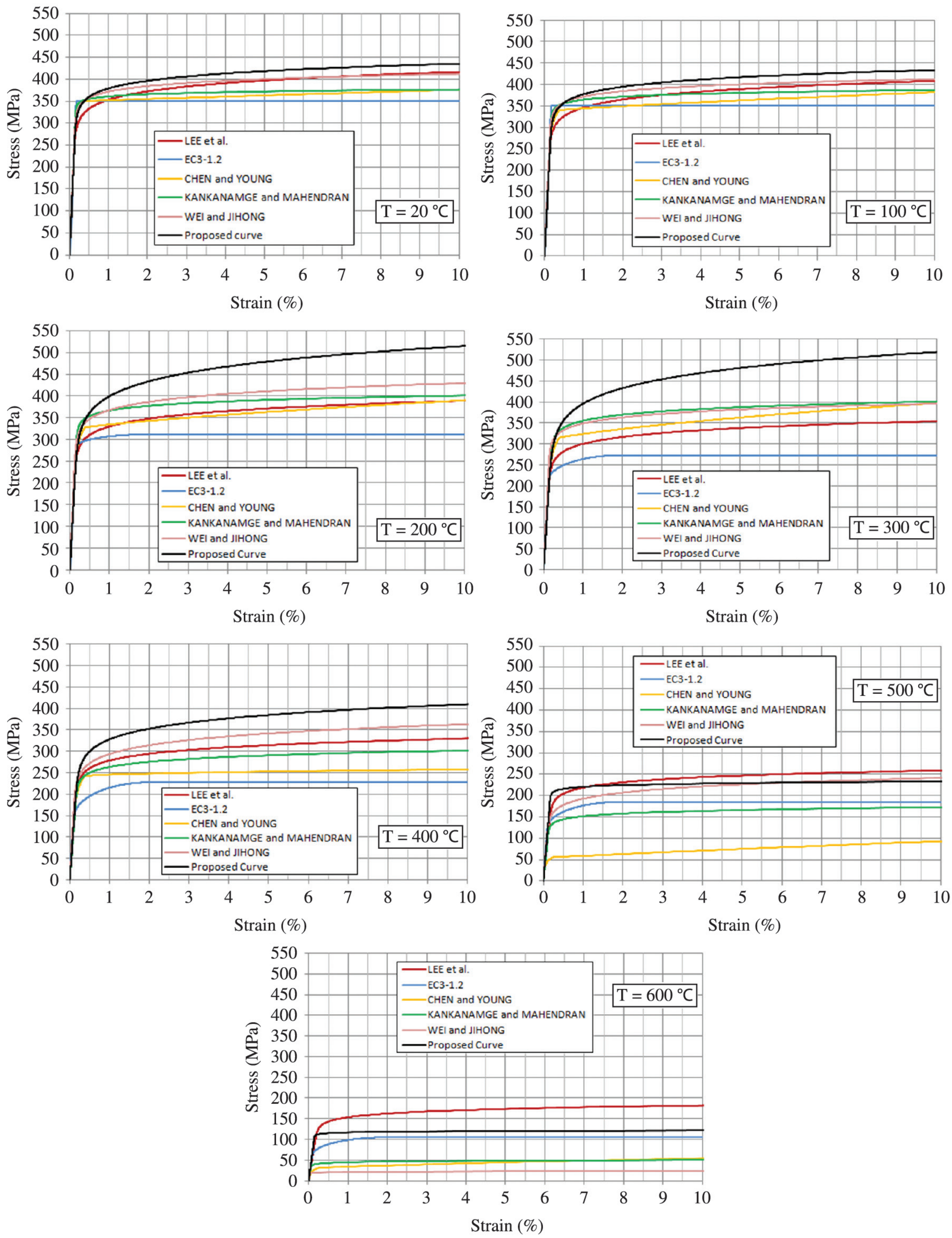

Figure 10. Stress-strain curves for each temperature, according with available and proposed models.

and proposed by Lee et al.[9] and Wei and Jihong[13] is 25 MPa, and for 400 °C, this value compared to Wei and Jihong[13] is 50 MPa. On the other hand, based on models of 500 °C, the behavior of the curve approach considerably from those proposed by Lee et al.[9] and Wei and Jihong[13] with a difference about 25 MPa from maximum stress values. Finally, in the case of 600 °C, the analytical model is positioned below the curve according Lee et al. (2003)[9] and very close to that recommended by EC3-1.2:2005[4], so that the difference between the maximum stress values is about 20 MPa.

The hardening effect observed in the behavior of the stress-strain-temperature curves obtained experimentally was represented by the analytical model for the temperatures from 20 °C to 400 °C. The proposed model also captured the elastic-plastic behavior of the curve at the temperature of 500 °C, as detected experimentally.

4. Final Remarks

This paper developed an experimental analysis to determine the constitutive relations of cold-formed steel ZAR-345 subjected to elevated temperatures. The behavior of the stress-strain-temperature curves was evaluated and the reduction factors values of mechanical properties were calculated in accordance with the results obtained directly from the experimental tests. Thus, an analytical model was proposed for the constitutive relations of cold-formed steel in function of temperature and the results were compared with models proposed by other authors and specifications of EC3-1.2:2005[4].

It was observed that there are clear differences between the reduction factors presented by different authors, the results obtained experimentally in this research and the recommendations of EC3-1.2:2005[4]. For cold-formed steel ZAR-345, the EC3-1.2:2005[4] recommends underestimated reduction factors of yield strength at all levels of temperature (up to 600 °C). However, for the reduction factors of elastic modulus, the EC3-1.2:2005[4] recommends overestimated values compared with most of the results obtained by the authors cited, including the factors obtained in this study. Only at temperatures between 500 °C and 600 °C, the values established by the standard resemble considerably with the factors obtained in this work.

It was confirmed that the cold-formed steel develops a different behavior from the hot-rolled steel, when both are subjected to equivalent elevated temperatures. The cold-formed steel suffers a greater loss of resistance and, therefore, it should be considered a compatible reduction of the mechanical properties. Another important observation is that the ductility increases in situations with higher temperatures, thus providing a possible useful benefic for the design of cold-formed steel structure in cases of fire.

Considering the behavior of the stress-strain-temperature curves, for cases with temperatures up to 400 ºC, the curves obtained according to the analytical model presented higher stress values than those adopted by other authors for the same strains, also accusing a hardening effect. In the analyzes with temperatures of 500 °C and 600 °C, the results demonstrated a proximity from the curves proposed by the researchers. It is considered that the test results data are enough accurate for other cold-formed steels with similar characteristics.

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