ДГКС
Друштво грађевинских конструктера Србије
ASES
Association of Structural Engineers of Serbia
S-1
15. KONGRES
6-8. 9. 2018. Zlatibor

Aljoša Filipović[1], Jelena Dobrić[2], Zlatko Marković[3], Dragan Buđevac[3], Nenad Fric[2], Milan Spremić[2]

EXPERIMENTAL INVESTIGATION OF COMPRESSED STAINLESS STEEL ANGLE COLUMNS

Summary:

This paper presents experimental program of ongoing scientific-research project that deals with behaviour analysis of compressed stainless steel columns with equal angle sections and which is being performed at University of Belgrade, Faculty of Civil Engineering. The project includes three types of steel products, hot-rolled, laser-welded and cold-formed members and two stainless steel grades, austenitic and lean-duplex alloys. The experiment covered all relevant tests: tensile coupon tests, stub-column tests and overall buckling tests of slender columns. Equal angle specimens of different overall slenderness were tested to determine both linear and nonlinear structural responses and failures, including flexural and torsional-flexural effects and the influences of the width-to-thickness ratios of the legs.

Key words: stainless steel, angle, compression, experiment, buckling, resistance

EKSPERIMENTALNO ISPTIVANJE PRITISNUTIH STUBOVA L PRESEKA OD NERĐAJUĆEG ČELIKA

Rezime:

Ovaj rad prikazuje eksperimentalni program tekućeg naučno-istraživačkog projekta koji se bavi analizom ponašanja pritisnutih stubova od nerđajućeg čelika ravnokrakog L poprečnog preseka, koji se sprovodi na Građevinskom Fakultetu, Univerzitetu u Beogradu. Projekat uključuje tri tipa čeličnih proizvoda, vruće-valjane, laserski-zavarene i hladno-oblikovane elemente i dve legure nerđajućeg čelika, austenitnu i niskolegiranu dupleks leguru. Eksperimentom su obuhvaćeni svi relevantni testovi: standardni testovi materijala na zatezanje, ispitivanje kratkih stubova na pritisak i ispitivanje globalne stabilnosti vitkih stubova. Uzorci ravnokrakog L poprečnog preseka različite vitkosti su testirani u cilju analize linearnog i nelinaernog konstruktivnog odgovora i oblika loma, uključujući efekte fleksionog i torziono-fleksionog izvijanja kao i uticaje vitkosti elemenata poprečnog preseka.

Ključne reči: nerđajući čelik, ugaonik, prtisak, eksperiment, izvijanje, nosivost

---

[1] *PhD student, University of Belgrade, Faculty of Civil Engineering, afilipovic@grf.bg.ac.rs*

[2] *Assistant professor, PhD, University of Belgrade, Faculty of Civil Engineering*

[3] *Full professor, PhD, University of Belgrade, Faculty of Civil Engineering*

1. INTRODUCTION

Single angle members exposed to compression have a traditional application in civil engineering mostly as members of different latticed structures or built-up columns. If these structures are in aggressive or urban environments, numerous stainless steel alloys may be beneficially utilized due to their corrosion resistance, attractive appearance, low maintenance requirements, good strength, toughness and fatigue properties.

Even though the geometry of angle section is simple, due to its asymmetry and distance between shear centre and centroid, the determination of the compressive capacity of angle columns may be complex. Furthermore, the angle members are usually eccentrically connected at their ends through one leg that introduce biaxial flexural deformation and consequently affect their ultimate structural responses. In general, failure of the centrically compressed angle member occurs due to flexural buckling about the minor principal axis of the cross-section or flexural–torsional buckling depending on its material response, cross-section slenderness, overall slenderness and boundary conditions.

The design of centrically compressed stainless steel angle members is not currently covered with European codified procedure. The lack of experimental data in this structural field results with the fact that the current design provisions in EN 1993-1-4 [1] rely solely on assumed analogies with the equivalent carbon steel members. Clause 5.4.1 [1] allows the use of appropriate provisions given in EN 1993-1-1 [2] and EN 1993-1-3 [3] for design of compressed stainless steels members but with modifications given in clause 5.4.2. However, the analytical method in clause 5.4.2 does not explicitly state the values of neither imperfection factor nor limiting slenderness for stainless steel angles in relevant buckling plane depending both on manufacturing process and steel grade. Exceptions from this rule are generally designated cold formed open sections. Thus, this kind of approach can lead to misconceived design practice since it does not offer clear response at the important issue related to application of corresponding design curve for reliable and safe prediction of buckling resistance of compressed stainless steel angle member.

An analytical method for design of centrically compressed members given in EN 1993-1-4 [1] is based on the Perry-Robertson equations and the linear expression for the imperfection parameter $\eta = \alpha\left(\bar{\lambda} - \bar{\lambda}_0\right)$. The influences of structure imperfections on the predicted flexural-buckling resistance is implicitly accounted for by employing an imperfection factor α associated with the appropriate buckling curve depending on the cross-section shape and manufacturing process. Besides, EN 1993-1-1 [2] stated additional rules for design single angle columns that are connected at their ends trough one leg by bolts or by welding. The procedure introduces an empirical equation for the non-dimensional effective slenderness ratio to account for both the end eccentricity and the end restraints.

Over the past two decades, significant attention has been paid to aspects of the potential use of stainless steel for construction purposes. However, none of the performed investigations was aimed at the buckling response of stainless steel angle columns. In order to fill this gap, the scientific-research project is being conducted at the University of Belgrade, Faculty of Civil Engineering. The project covers investigative and experimental work with the aim of acquiring further knowledge to facilitate the development of design procedures for compressed stainless steel angles. The research focuses on different material and geometrical parameters of the selected stainless steel equal angles produced from austenitic and lean-duplex stainless steel alloy. To assess impacts of the initial imperfections on column compressive resistance that caused by different manufacturing procedures, three types of angle products are included: cold-formed, hot-rolled and laser-welded sections. Hence, the important innovative content of the project relates to extension of the scope of the current codified procedures in EN 1993-1-4 [1] not only to conventional angle profiles but also to the contemporary products such as the laser-welded angles. To determine both elastic and non-elastic ultimate responses including flexural and torsional-flexural modes and effects of cross-section slenderness, the equal angle specimens are selected to cover whole overall slenderness range.

2. EXPERIMENTAL TESTING

This paper describes a part of performed experimental investigation including material tests and overall buckling tests of slender pin-ended columns, addressing their flexural buckling capacity about the minor principal axis. The experiment aims at understanding the effects of the material nonlinearity, structural imperfections and cross-section slenderness on the ultimate behaviour of stainless steel angle columns.

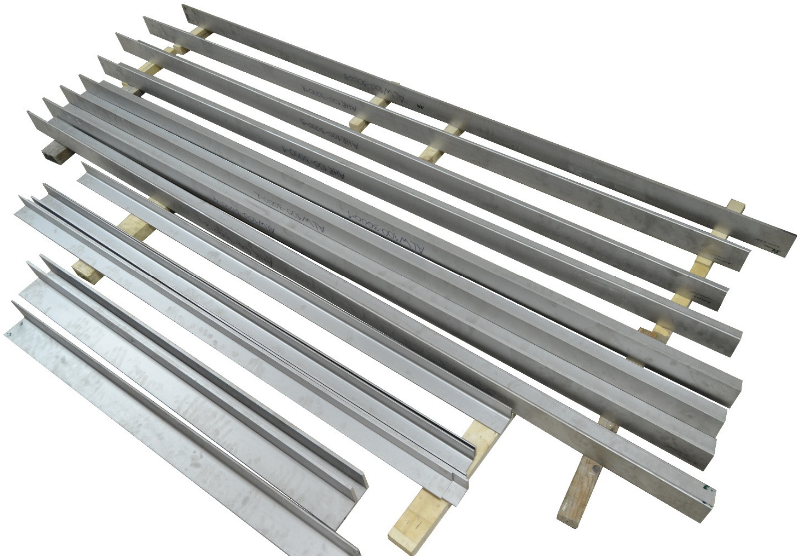
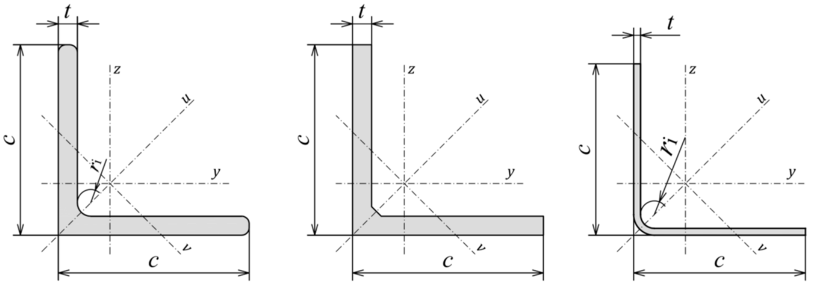


Figure 1 – Specimens used in experiment

The test specimens are equal stainless steel hot-rolled, laser-welded and cold-formed angle products, as shown in Fig. 1. The basic material of hot-rolled and laser-welded specimens is the most commonly used austenitic stainless steel grade EN 1.4301 (X5CrNi18-10). The cold-formed specimens are press-braked from flat strips of lean-duplex stainless steel EN 1.4162 (X2CrMnNiN21-5-1) as slender angle sections.

According to EN 1993-1-4 [1], the hot-rolled and laser-welded specimens are classified as semi-compact sections while cold-formed angles satisfy requirements for slender sections. The buckling behaviour of members in both linear and non-linear stress domain is achieved through the careful selection of the range of member overall slenderness. The scale of the tested members corresponds to the real structural elements that have the use in civil industry. Considering type of steel product, cross-sections' dimensions and specimens' lengths, the total number of 48 specimens are divided into 12 tested series, each includes four repeated tests. The sectional geometric parameters of each tested product are illustrated in Fig. 2, while Table 1 summarizes the nominal geometrical dimensions of the specimens including overall slenderness ratio about minor principal axis.



(a) hot-rolled angle *(b) laser-welded angle* *(c) cold-formed angle*

Figure 2 - Cross-sections of the angle specimens

Table 1 - Nominal geometry and slenderness ranges of specimens in the experiment

Designation of specimen series	*Stainless steel grade*	*Stainless steel product*	*Specimen geometry*			*Slenderness ratio λ_v*	*Number of repeated tests*
			Leg width c (mm)	*Thickness t (mm)*	*Length L (mm)*		
AHR 100	*EN 1.4301*	*Hot-rolled*	*100*	*10*	*500*	*26*	*4*
					1500	*77*	*4*
					2500	*128*	*4*
AHR 60	*EN 1.4301*	*Hot-rolled*	*60*	*6*	*800*	*70*	*4*
					2000	*170*	*4*
ALW 100	*EN 1.4301*	*Laser-welded*	*100*	*10*	*500*	*25*	*4*
					1500	*76*	*4*
					2500	*127*	*4*
ALW 60	*EN 1.4301*	*Laser-welded*	*60*	*6*	*800*	*68*	*4*
					2000	*172*	*4*
ACF 80	*EN 1.4162*	*Cold-formed*	*80*	*4*	*1000*	*65*	*4*
					2000	*130*	*4*

The specimens' geometry was controlled by direct mechanical measuring to determine the variation between the actual and nominal specimen dimensions.

The experimental data are used to establish qualitative data base through numerical simulations of experiments and to perform a quantitative numerical parametric study to enable accuracy assessment of buckling curves given in EN 1993-1-1 [2] for design of stainless steel angle columns.

2.1 MATERIAL PROPERTIES

The investigation is concentrated on the austenitic stainless steel grade EN 1.4301 and lean-duplex grade EN 1.4162 that typically used in structural applications.

Three coupons were longitudinally cut from both legs of hot-rolled and laser-welded specimens, respectively (see Fig. 3). To asses anisotropy of stainless steel and consider influence of cold working on the material response of the final press-braked sections, two test series are carried out. The first series included six flat coupons taken from the flat steel sheets in both longitudinal and transverse roll direction. The second series included three flat coupons longitudinally cut from the legs and two corner coupons used within the boundary of the internal radius of the cross-section's corner region of press-braked angle specimen. All coupons were cut by a water jet cutter to decrease heating of material during their preparation. The coupons were tested in accordance with EN ISO 6892-1 [4]. Tensile testing of coupons was performed at the University of Belgrade, Faculty of Technology and Metallurgy. The tests were carried out on the Shimadzu Universal Testing Machine AG-Xplus. Fig. 4 shows the setup for tensile coupon test.

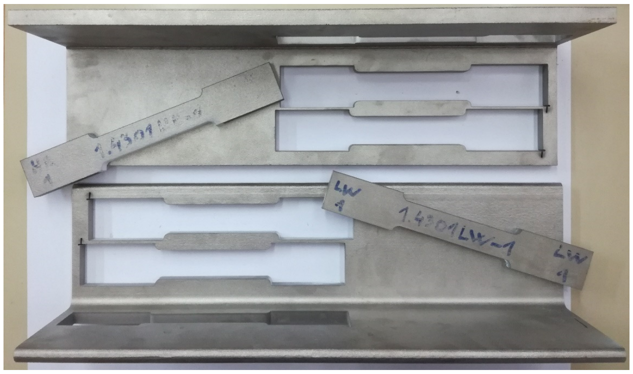
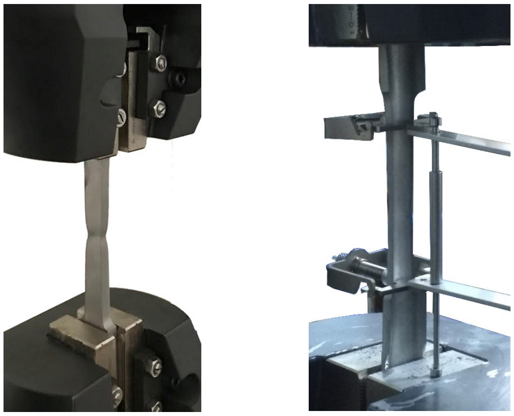


Figure 3 – Location of coupons from hot-rolled and laser-welded angle specimens

The tests provided engineering stress–strain curves and determined the most important material properties: yield strength f_y used as 0.2% proof stress $f_{0.2}$, ultimate tensile strength f_u, strain corresponding to the ultimate tensile strength ε_u, total strain at fracture ε_f and modulus of elasticity E. The obtained engineering stress–strain curves and the mean values of the key material properties for hot-rolled angles are provided in Fig. 5. It can be seen from Fig. 5 that austenitic stainless steel EN 1.4301 exhibits a rounded nonlinear stress–strain relationship with gradual yielding and almost twice higher ductility than the typically used carbon steels. The results also showed that the measured yield strengths of austenitic stainless steel exceed the nominal value stated in EN 10088-2 [5] with difference of 40 %.



(a) flat coupon *(b) corner coupon*

Figure 4 – Tensile test setup

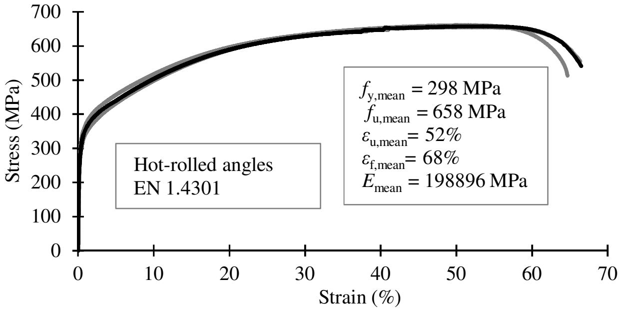
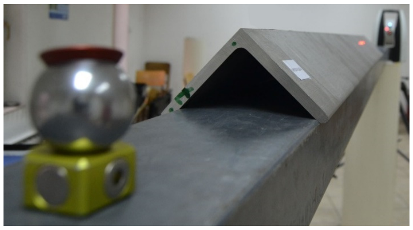


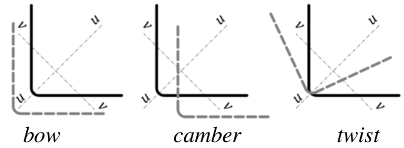
Figure 5 – Engineering stress-strain curves for hot-rolled angles

2.2 MEASUREMENT OF GEOMETRIC IMPERFECTIONS

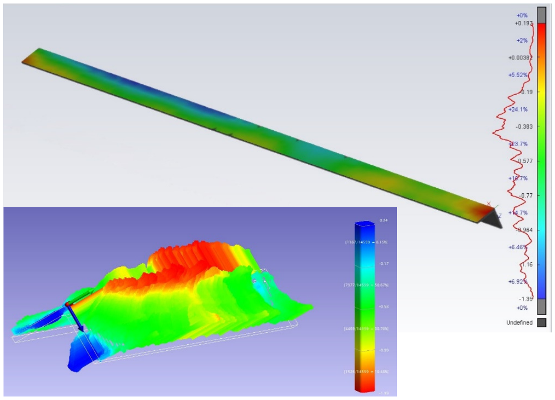
The initial geometric imperfections of real structural elements introduce bending from the onset of loading and therefore strongly affect the ultimate buckling response of a column. To measure geometric imperfections, a laser measurement system with Leica Absolute Tracker AT930 was used. The fields of geometric imperfections were obtained by laser scanning the specimen at leg multiplanes and registering the individual scans into the same final global coordinate system. The colour distributions of scanned segments are based on deviation from nominally expected dimensions. One of benefits of used laser measuring system is the determination of deviation between the centroid axes of element with real geometry and its equivalent element with idealized nominal geometry. Dimensional variations that may be considered as cross-section's imperfections lead to initial curvature of the centroid axis and contribute to changes in the strength and flexural rigidity of the structural element. Three types of overall geometric imperfections were identified from the measurement points: measurements normal to minor axis – bow imperfections, measurements normal to major axis – camber imperfections and twist imperfections. Fig. 6 shows the laser measurement system, example of three-dimensional geometric imperfection scans and types of overall geometric imperfections.



(a) laser measurement system



(b) overall imperfections



(c) imperfection colour distribution of scanned segments

Figure 6 – Method for measuring initial geometric imperfections of angle specimens

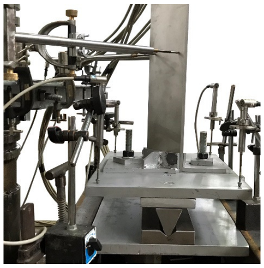
2.3 BUCKLING TESTS

The buckling tests of specimens were carried out at the Laboratory for Testing of Structures at the Institute for Testing of Materials in Belgrade. The specimens were tested under concentric compression loading using a hydraulic testing machine with fixed plates and a capacity of 5000 kN. All tests were performed monotonically using displacement control with a proper loading rate not exceeding 0.01 mm/s up to the maximum load capacity, and then continued up to approximately 70% of the maximum load before stopping the test.

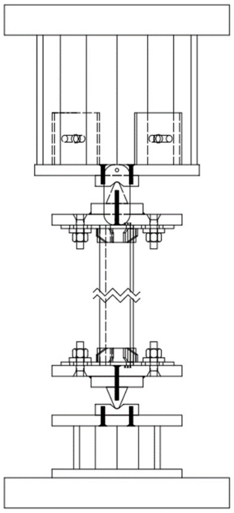
Taking into account the specific geometry of angle section, direction of its principle axis and distance between section's shear centre and centroid, to provide pin-ended boundary conditions during testing was challenging. Hence, the lubricated spherical steel supported plates were utilized to provide a rotation about minor principle axis during the test. In the test set-up, the specimens were carefully aligned to ensure that the load application points at each end would be at the centroid of the angle section. After the alignment of the specimen in the testing machine, the ram of the actuator was moved slowly toward the specimen until the base plate was in full contact with the bottom specimen's end having a small initial load of approximately 3 kN. At this load, all instrumentation was adjusted for measuring the axial load, lateral deflections and axial strains.

(a) LVDTs at mid-height of specimen

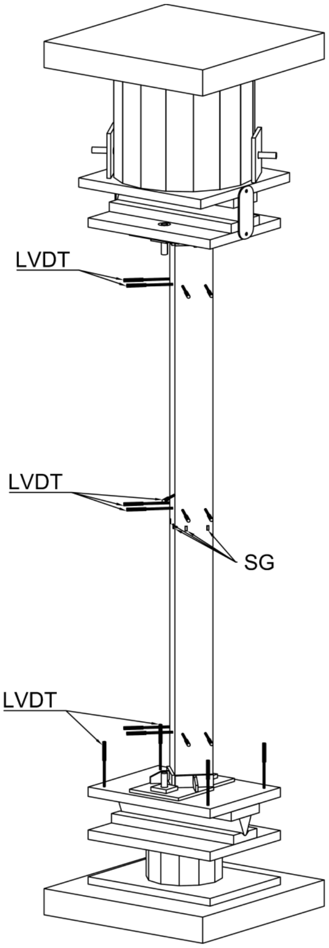
(b) LVDTs and SGs at mid-height and upper end of specimen



(c) LVDTs at bottom end of specimen and bottom bearing plate



(d) upper and bottom bearing plates



(e) test setup

Figure 7 – Instrumentation layout and test setup

The critical cross-section was expected to be at or near the mid-height of the column, thus the lateral movements and axial strains were therefore measured at this sections for all tested columns. To record both flexural and torsional movements of the specimen cross-sections, four longitudinal displacement transducers (LVDTs) were attached perpendicular to each leg at mid-height and near to the ends of specimens. The displacement in the expected buckling plane perpendicular to minor principal axis was also measured with additional LVDT at the mid-height of specimens. Besides, four LVDTs were mounted on the bottom bearing plate to record its rotations and displacements. Axial strains were monitored by strain gauges (SGs) attached around the perimeter surface of the cross-section at the specimens' mid-height.

A calibrated load cell C6A Force Transducer was used to measure the applied load. A data acquisition system was used to record the applied load, LVDTs and strain gauge readings during the tests. Fig. 7 shows the detailed instrumentation layout and test setup.

(a) local buckling columns of low slenderness

(b) flexural buckling columns of intermediate slenderness

(c) flexural buckling columns of high slenderness

Figure 8 – Typical failure modes of the selected angle specimens

The obtained experimental results clearly showed different ultimate structural responses of angle columns with pin-ended boundary conditions. Depending of the overall slenderness ratios, width-to-thickness ratios of the legs and initial eccentricity conditions, the specimens failed in flexural, torsional-flexural, and coupled flexural/torsional-flexural modes. The local buckling failure characterized by distortion of the cross-section was dominant mode for hot-rolled and laser-welded specimens in the low slenderness range ($\lambda_v = 25$). In the intermediate slenderness range ($\lambda_v = 76$), the inelastic flexural buckling about minor principal axis was notified for the same stainless steel angle products. Contrary, the overall compressive capacity of the cold-formed angles ($\lambda_v = 65$) was limited by the capacity of the individual section elements. The failure mode was interaction of the local and overall flexural buckling. The largest number of the most slender hot-rolled and laser welded angle specimens (λ_v = 170) had pure flexural buckling about minor axis. In the case of cold-formed stainless-steel angles (λ_v = 130), it was observed that the influence of section slenderness on the ultimate flexural buckling response is not explicitly evident. Typical deformed shapes of the selected specimens after buckling are shown in Fig. 8.

3. CONCLUSIONS

The presented ongoing project is planned as a pre-normative research aiming to propose initial criteria for design of compressed structural members with equal angle-sections for the next version of EN 1993-1-4. Following the extensive experimental programme supported by theoretical and numerical analysis, buckling curves referred to different manufactured performances of angle members will be developed. By providing the integration of gained outcomes in the Eurocode 3, this project will generate a wider range of economic benefits for manufacturers, users and designer across the European construction industry.

ACKNOWLEDGEMENTS

This investigation is supported by the Serbian Ministry of Education, Science and Technological Development through the TR-36048 project. The authors are grateful to chair of the Eurocode Working Group for EN 1993-1-4 Nancy Baddoo, to companies Montanstahl ag Switzerland, Armont SP Belgrade, Institute for Testing of Materials Belgrade, Institute for Materials and Structures Faculty of Civil Engineering University of Belgrade, Vetroelektrane Balkana Belgrade, ConPro Novi Sad, Energoprojekt Industrija PLC Belgrade, Vekom Geo Belgrade, Peri Oplate Belgrade, North Engineering Subotica, Amiga Kraljevo, Mašinoprojekt kopring PLC Belgrade, Sika Belgrade, DvaD Solutions Belgrade and Soko Inžinjering Belgrade for their support.

REFERENCES

[1] Eurocode 3, Design of Steel Structures – Part 1-4: General Rules – Supplementary Rules for Stainless Steels, Including Amendment A1, CEN, Brussels, Belgium, 2015 EN 1993-1-4:2006+A1:2015.

[2] Eurocode 3, Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings EN 1993-1-1, CEN, Brussels, Belgium, 2005.

[3] Eurocode 3, Design of Steel Structures – Part 1-3: General rules — Supplementary Rules for Cold-formed Members and Sheeting EN 1993-1-3, CEN, Brussels, Belgium, 2006.

[4] EN ISO 6892-1, Metallic materials — tensile testing, Part 1: Method of Test at Room Temperature. European Committee for Standardization, CEN, Brussels, 2009

[5] EN 10088-1:2005: List of stainless steels; EN 10088-2:2005: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for general purposes; EN 10088-3:2005: Stainless steels, Technical delivery conditions for semifinished products, bars, rods and sections for general purposes, CEN, Brussels, 2005.