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NOSIVOST RAZLIČITIH TIPOVA RAVNOKRAKIH UGAONIKA OD NERĐAJUĆEG ČELIKA PRI DEJSTVU CENTRIČNOG PRITISKA

Rezime:

U važećem evropskom standardu SRPS EN 1993-1-4 nisu eksplicitno definisana pravila za proračun centrično pritisnutih elemenata ravnokrakog L poprečnog preseka od nerđajućeg čelika. Ovaj rad ukratko prikazuje rezultate opsežnog istraživanja sprovedenog na ovom tipu konstruktivnih elemenata sa ciljem definisanja preporuka za njihov proračun. Istraživanje je sprovedeno na Univerzitetu u Beogradu na Građevinskom fakultetu i publikovano u doktorskoj disertaciji „Nosivost različitih tipova ravnokrakih ugaonika od nerđajućeg čelika pri dejstvu centričnog pritiska“. Analizirana su tri tipa čeličnih proizvoda, vrućevaljane, laserski zavarene i hladnooblikovane elemente i dve legure nerđajućeg čelika, austenitna i niskolegirana dupleks legura. Na osnovu sistematičnog eksperimentalnog istraživanja i detaljne numeričke analize preporučene su krive izvijanja za kontrolu stabilnosti na fleksiono i fleksiono-torziono izvijanje u skladu sa evropskim proračunskim procedurama.

Ključne reči: Nerđajući čelik, Ugaonik, Fleksiono izvijanje, Torziono-fleksiono izvijanje

RESISTANCE OF DIFFERENT TYPES OF STAINLESS STEEL EQUAL ANGLES UNDER AXIAL COMPRESSION

Summary:

The current European standard SRPS EN 1993-1-4 does not explicitly define the rules for the the design of stainless steel axially compressed equal angle columns. This paper briefly presents the results of extensive research conducted on this type of structural elements with the aim of defining recommendations for their design. The research was carried out at University of Belgrade, Faculty of Civil Engineering and published in PhD thesis "Resistance of different types of stainless steel equal angles under axial compression". Three types of steel products (hot-rolled, laser-welded and cold-formed) and two stainless steel alloys (austenitic and low alloy duplex steel) were analysed. Based on systematic experimental research and detailed numerical analysis, buckling curves were recommended for stability control in flexural and flexural-torsional buckling in accordance with European design procedures.

Key words: Stainless steel, Angle, Flexural buckling, Torsional-flexural buckling

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1. INTRODUCTION

In the last decades technological progress has led to wider application of stainless steel in modern structural engineering. Structural behaviour of this material differs significantly from that of carbon steels. There are many benefits of stainless steel which make it desirable for use in offshore platforms, industrial facilities in aggressive environments and bridge structures. Most important properties that make this material superior to carbon steel are: attractive surface appearance that does not require protective coatings, high corrosion resistance, significant plastification capacity, pronounced ductility and high values of yield and tensile strength. Also, stainless steel belongs to a group of clean materials and it is often used for load-bearing structures of tanks and silos for food, liquids and medical remedies storage. Like any structural material, its application is the construction industry is dictated by the technical design regulations. Continuous research of stainless steel elements behaviour is of outmost importance for development of new and improvement of the existing design regulations for stainless steel structures.

Axially loaded elements of trusses, bracings and telecommunication towers are very often made of steel angles. However, existing international standards for the design of stainless steel structures do not provide explicit rules for axially compressed angles, due to insufficient number of relevant studies. Comprehensive research is necessary in order to determine accurate behaviour of stainless steel angles in terms of ultimate bearing capacity and fracture modes.

This paper presents a scientific research on axially compressed pinned angle columns performed at University of Belgrade, Faculty of Civil Engineering. Experimental and numerical analysis were performed to obtain relevant and reliable data that will define guidelines and rules for the design of axially compressed angle columns, considering differences caused by production methods. This research included cold-formed, hot-rolled and laser welded angles in order to determine dependence of initial structural imperfections from production technology. Two stainless steel alloys, low alloy duplex steel EN 1.4162 and austenitic stainless steel EN 1.4301 were considered. The experimental program consisted of determining mechanical properties, bearing capacity, initial geometric imperfections, values and distribution of residual stresses and global forms of instability and flexural and flexural-torsional buckling capacity.

Numerical models based on finite element method were developed in software package Abaqus [1] and calibrated and validated. Developed models were calibrated and validated through comparison with the experimental results. Extensive parametric numerical studies of effects of global slenderness and cross-sectional slenderness on the response of elements in a state of ultimate bearing capacity were performed. Based on these results a comprehensive and reliable database was formed which enabled (1) verification of international standardized methods for the design of axially compressed stainless steel elements and (2) basis for mathematical interpretation of the elements load-bearing capacity and defining appropriate recommendations for their design in accordance with the implemented procedures of European standards for steel load-bearing structures. Furthermore, based on this research development of new buckling curves for each type of angles – cold-formed, hot-rolled and laser-welded for lean-duplex alloy and austenitic stainless steel alloy was made possible.

The analytical background, state of art, experimental procedures, numerical studies and used methodologies are described in detail in recently published papers [2], [3], [4], [5] and [6].

2. EXPERIMENTAL STUDY

A systematic experimental programme was performed to examine the structural behaviour of pin-ended angle columns. The experimental research consisted of a series of tensile material tests, residual stress measurements, compressive stub column tests and global buckling tests. All the tests were performed on hot-rolled and laser-welded equal-angle angles with nominal section dimensions 60 × 60 × 6 mm and 100 × 100 × 10 mm produced from austenitic stainless steel grade EN 1.4301 and press-braked angles from high strength lean-duplex stainless steel grade EN 1.4162 with nominal section dimensions 80 × 80 × 4 mm. All the specimens had a designation AAA b × b × t – L – X where the first letters "AAA" indicate acronym of angle hot-rolled (AHR), laser-welded (ALW) or cold-formed (ACF) section, "b" and "t" respectively represent leg width and leg thickness, "L" is the length of the specimens and "X" is a sequential number from 1 to 4, which relates to the repeated specimens within one tested group.

2.1 MATERIAL TESTS

In order to determine material properties of the two considered stainless steel alloys, tensile coupon tests were carried out. The hot-rolled and laser-welded specimens were made of austenitic stainless steel grade EN 1.4301 (X5CrNi18-10), while the cold-formed specimens were press-braked from flat strips of lean-duplex stainless steel EN 1.4162 (X2CrMnNiN21-5-1).

Three flat coupons were cut from both legs of hot-rolled and laser-welded specimens in the longitudinal direction. The material tests on cold-formed angle specimens included two 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. All coupons were cut by a water jet cutter to decrease heating of the material during preparation. The coupons were tested in accordance with EN ISO 6892-1 [7]. The obtained engineering stress–strain curves for all three types of angle products are provided in Figure 1.

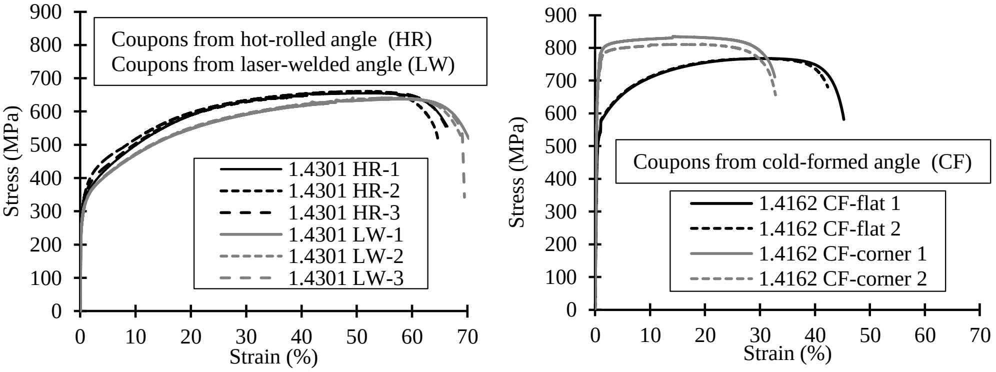
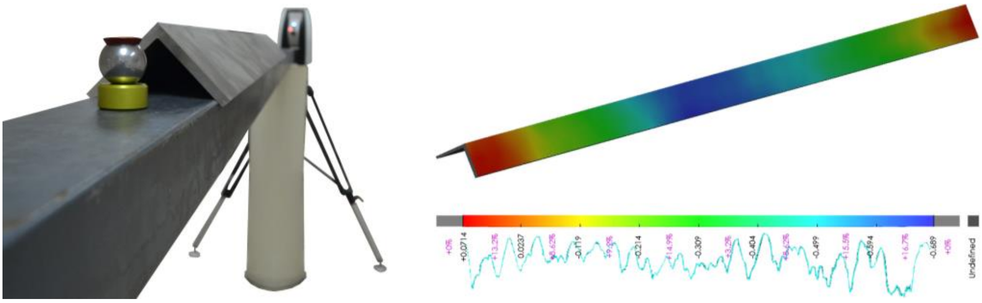


Figure 1 - Engineering stress-strain curves [8]

The measured yield strengths of austenitic stainless steel for hot-rolled and laser-welded angles exceeded the nominal value for stainless steel sections given in EN 1993-1-4 [9] by 52% and 30%, respectively. In case of duplex stainless steel used for cold-formed angles this margin is lower, up to 7% for flat coupons. The enhanced yield strength of the corner regions is approximately 38% higher in comparison with the strength of flat materials.

2.2 MEASUREMENT OF GEOMETRIC IMPERFECTIONS

The very important aspect of the research included accurate determination of specimens' geometry and initial imperfections. A multiplanar laser tracker system was employed for these measurements. To quantify imperfections a commercial laser tracker, the Leica Absolute Tracker AT960 (Hexagon Manufacturing Intelligence, UK) with a spherically mounted retroreflector, was used (see Figure 2a). Geometric data for full field of a target specimen was demonstrated as a point-grid by measuring the outer surface of the specimen at multiplanes of view and recording the individual set of measurements into the same final global coordinate system. The measured segments were entered in the global coordinate system and then coloured based on deviation from nominal specimen geometry (see Figure 2b).



a) Laser tracker setup with installed specimen

b) 3D reconstructed model of specimen ALW 100 × 100 × 10 – 1500 – 3

Figure 2 - Measurement of geometric imperfections [5]

Local imperfections related to cross-section distortion and overall imperfections related to bow, camber and twist were identified from the measurement point-grids. All amplitudes of initial imperfections of the specimens were considerably lower than the maximum fabrication tolerances permitted for steel profiles.

2.3 MEASUREMENT OF RESIDUAL STRESS

Equally important measurement for this research was determination of residual stresses. Using the sectioning method at room temperature, the longitudinal residual stress patterns in both hot-rolled and laser-welded stainless steel equal angles with nominal dimensions 100 x 10 mm (austenitic grade EN 1.4301) were measured. The sectioning method consists of abrasive water jet cutting that utilizes a high velocity stream of abrasive particles suspended in a stream of high-pressure water. The test area was at a distance of 3 times the leg width from the specimen ends so as to reduce end effects. Both outer and inner surfaces of legs of each angle specimen were equipped with 40 waterproof strain gauges in total. The strain gauges were attached in pairs on the opposite leg sides except in the angle heel area. The specimens were clamped, and cut transversely in two pieces after which most of the residual stresses were relieved. Afterwards, the subsequent 40 mm long longitudinal cuts were made to relieve the remaining stresses (see Figure 3). To account for any temperature changes, a temperature reference bar was used. Strain measurements were recorded during the entire cutting procedure and approximately 30 min after the cutting was finished. The residual stresses were calculated by multiplying the released strains with modulus of elasticity.

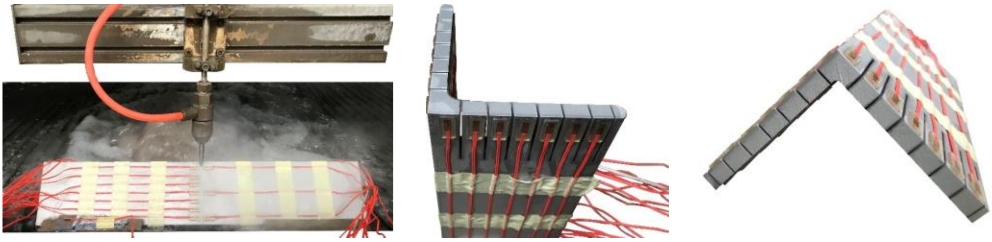
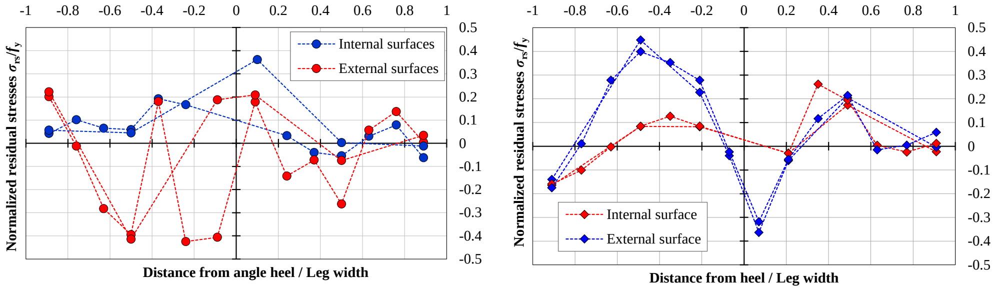


Figure 3 - Measurement of residual stress - sectioning method

Distribution of normalized residual stresses for hot-rolled and laser-welded stainless steel specimens, normalised by the material yield strength, are presented in Figure 4.

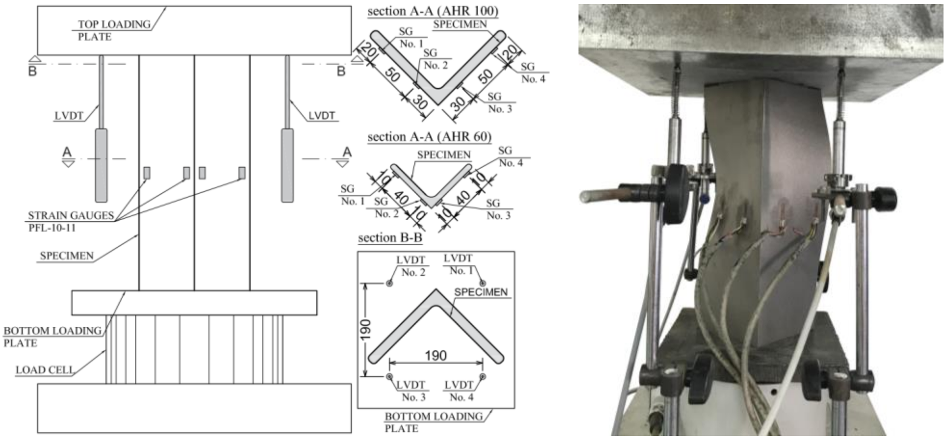


a) Hot-rolled specimen *b) Laser-welded specimen*

Figure 4 - Distribution of normalized residual stresses along the angle leg width

2.4 STUB COLUMN TEST

The stub column tests on three specimens of each size of angle products (hot-rolled, laser-welded and cold-formed were performed in accordance with clause A.3.2.1, EN 1993-1-3 [10] to assess their cross-section resistance.



a) Instrumentation configurations *b) Test setup*

Figure 5 - Test setup for stub column specimens [4]

The end plates of the testing machine were positioned flat and parallel. Longitudinal displacement transducers (LVDTs) were used to measure end shortening of the specimens and four linear electrical strain gauges (SGs) were used to measure strains at mid-height. Figure 5 depicts the experimental setup and failure mode of hot-rolled specimen.

The failure mode of hot-rolled and laser-welded angle specimens was inelastic local buckling of the legs, while cold-formed angles had an elastic local buckling response at the ultimate limit state. For all specimens, buckling was localised in the middle and characterised by the torsion deformations of angle legs.

2.5 GLOBAL BUCKLING TESTS

Experimental research in order to determine the compressive response of the slender pin-ended angle columns included a total of 48 specimens. The specimens were divided into 12 series varying the type of steel product, cross-sections' dimensions and specimens' lengths. Each series each included four repeated tests. The test setup and mounted instrumentations are all illustrated in Figure 6.

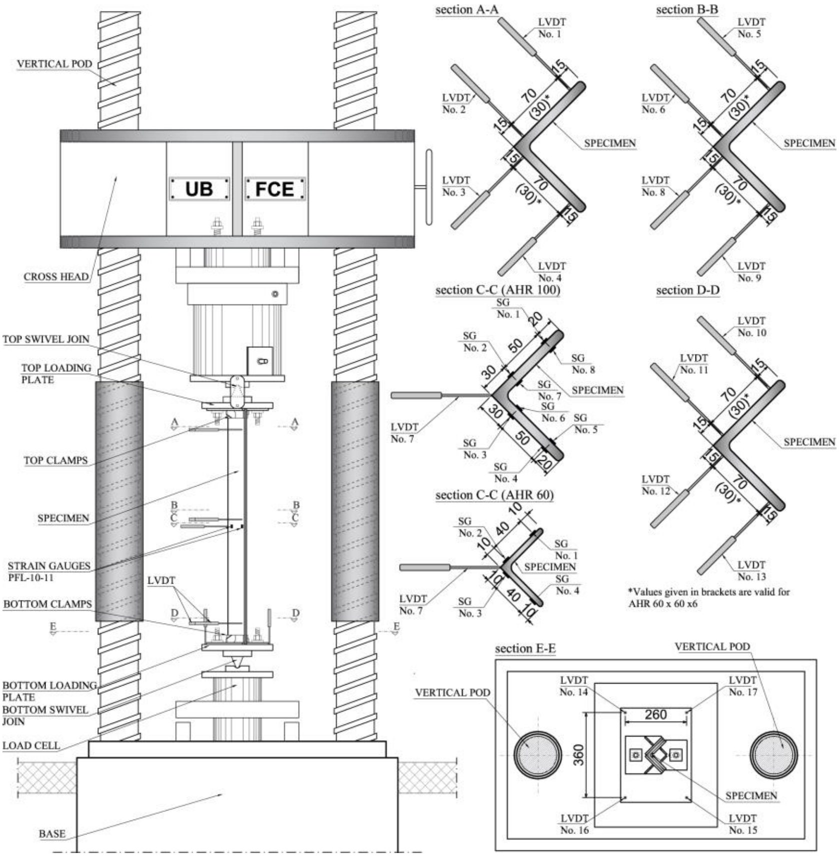


Figure 6 - Test setup for and instrumentation configuration for global buckling tests [4]

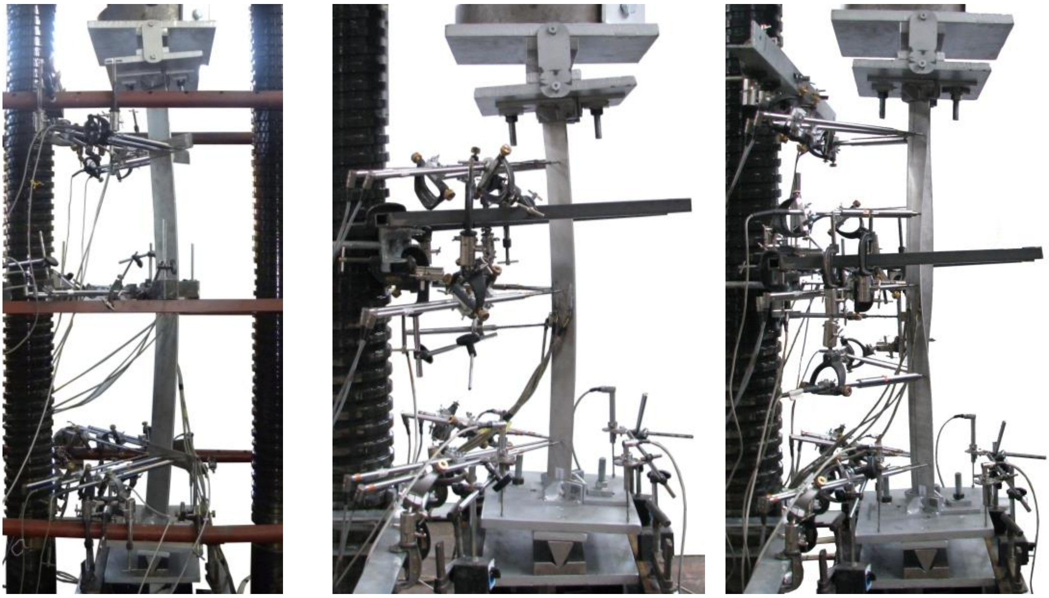
The specimens were tested under concentric compression loading using a hydraulic testing machine with a capacity of 5000 kN. The tests were performed monotonically using displacement control to the maximum load capacity and continuing up to approximately 70% of the maximum load before stopping the test. Loading rate did not exceed 0.01 mm/s.

The pin-ended bearings allowed rotations about the minor axis, while restraining major axis rotations as well as twist rotations. The specimens were positioned so that their minor principal axis coincided with the axis of the support rotation, affecting the bending of the specimen about the minor axis. LVDTs were used to record flexural and torsional movements of the specimen cross-sections, the displacement in the expected buckling plane perpendicular to the minor principal axis, bottom bearing plate's rotations and displacements; SGs were used to measure axial strains and a calibrated load cell C6A Force Transducer was used to measure the applied load. Data acquisition system recorded the applied load, LVDTs and SGs readings during the tests.

The specimens failed in flexural, torsional-flexural, and coupled flexural/torsional-flexural modes, depending on the overall slenderness ratios, width-to-thickness leg ratios and initial eccentricity conditions. Typical deformed shapes of selected specimens after buckling are shown in Figures 7–9.

AHR 100 × 100 × 10 – 500 – 2 *AHR 100 × 100 × 10 – 500 – 3* *ALW 100 × 100 × 10 – 500 – 1*

Figure 7 - Typical failure modes of short length specimens



AHR 100 × 100 × 10 – 1500 – 2 *ALW 60 × 60 × 6 – 800 – 3* *ACF 80 × 80 × 4 – 1000 – 3*

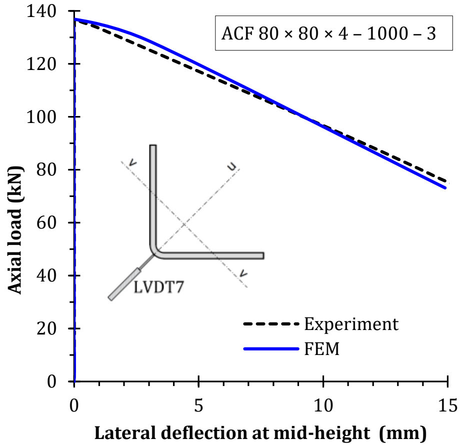
Figure 8 - Typical failure modes of intermediate length specimens

AHR 60 × 60 × 6 – 2000 – 2 *ALW 60 × 60 × 6 – 2000 – 2* *ACF 80 × 80 × 4 – 2000 – 4*

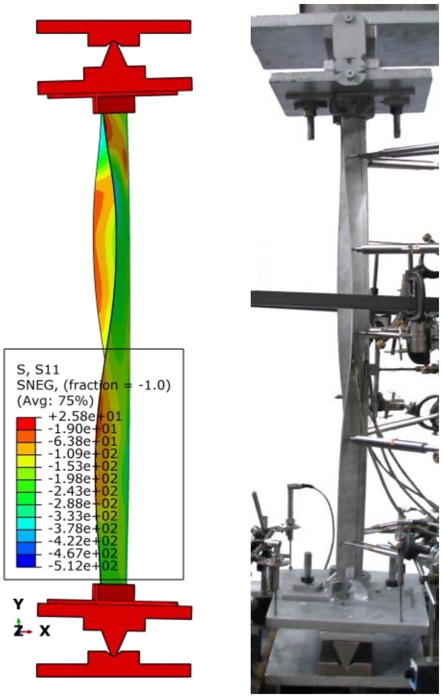
Figure 9 - Typical failure modes of long length specimens

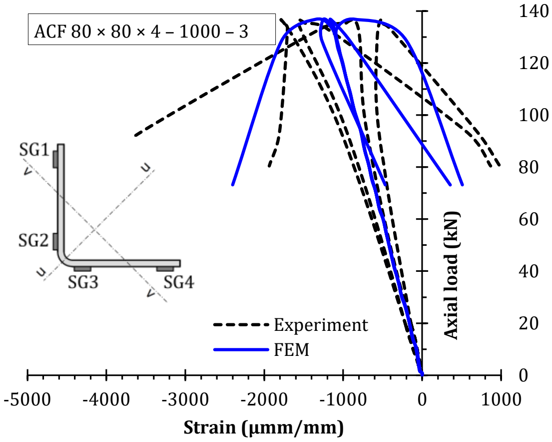
3. FINITE ELEMENT MODELLING AND PARAMETRIC STUDY

Finite element based software package Abaqus [1] was employed for the numerical simulations of the experiments performed on equal angle columns.



(b) Load vs. lateral deflection





(a) FTB mode ACF 80 × 80 × 4 – 1000

(c) Load vs. axial strains

Figure 10 - FE model and experimental buckling mode of intermediate length specimens [3]

The geometrically and materially non-linear analysis (GMNIA) was developed as quasi-static with the dynamic explicit solver and the variable non-uniform mass scaling technique. The S4R shell elements were used for modelling of cold-formed columns and the C3D8R solid elements were adopted to model hot-rolled and laser-welded columns. To accurately simulate the pin-ended supporting conditions in global buckling tests, the hardened steel knife-edge devices attached to steel loading plates, together with top and bottom adjustable clamps were additionally modelled using four solid elements C3D8R. To model material properties of steel end adjustable clamps (S275JR) and the hardened steel knife-edges (S355N), a linear elastic–perfectly plastic material model with a nominal plateau slope was used. Material properties of angles flat legs and corner were imported from the measured stress–strain curves obtained via flat and corner tensile coupon tests. The initial geometric imperfections were explicitly modelled using the lowest local (twist imperfection ─ local/torsional mode) and global (bow imperfection about the minor-principal axis) buckling modes obtained via Linear Buckling Analysis (LBA) performed on equivalent FE models with the same mesh. The imperfection amplitudes matched the measured ones. The 3-point linear model, based on measurements made on hot-rolled and laser-welded equal-leg angle columns was used to define distributions and magnitudes of residual stresses in the FE models in this study.

The qualitative comparisons of the FE model and experimental buckling mode of intermediate length specimens are presented in Figure 10.

Once the developed FE models were verified through the comparison with the experimental results, they were employed to perform an extensive parametric study. The aim of this study was to thoroughly examine the structural responses of cold-formed, hot-rolled and laser-welded equal angle columns. The wide range of columns' global slenderness was considered in the study to investigate LB, major-axis FTB and minor-axis FB resistances. Figure 11 presents a comparison between the results of the FE parametric study and those obtained using EN 1993-1-4 [9] and AISC 27 [11] for minor-axis FB of hot-rolled angle columns, while Figure 12 presents the comparison of the results of the FE parametric study and those obtained using EN 1993-1-4 [9] for FTB of cold-formed angle column.

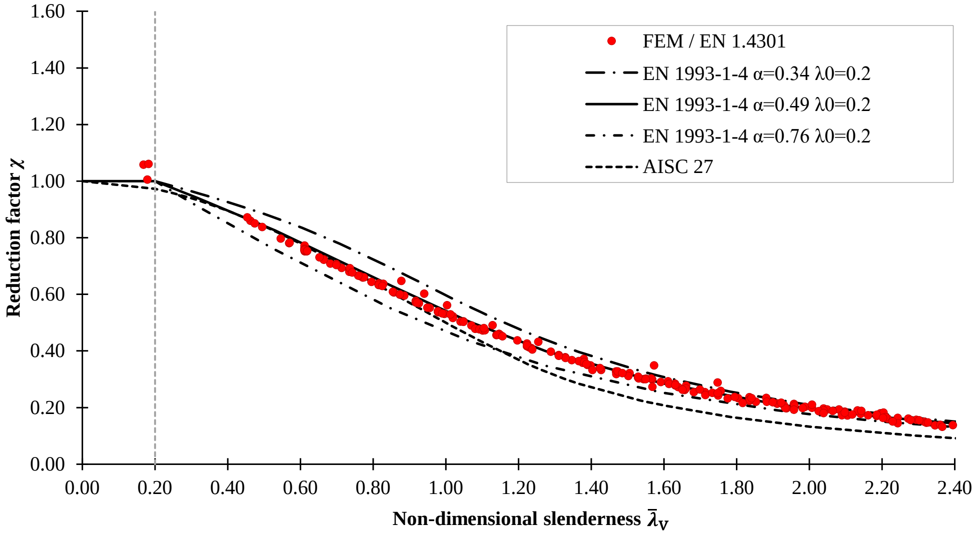


Figure 11 - Comparison of normalised FE data against those obtained using EN 1993 - 1 - 4 and AISC 27 for minor-axis FB of hot-rolled angle columns

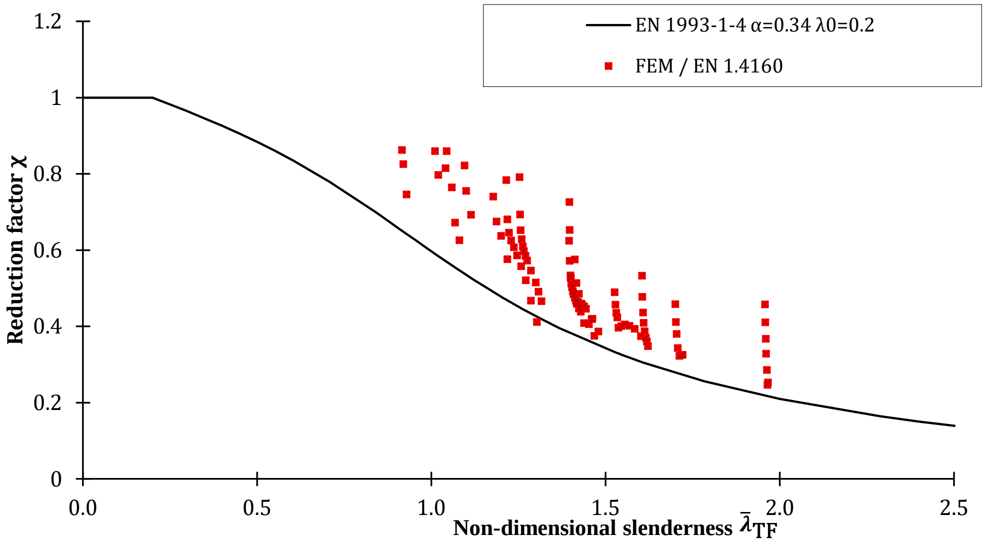


Figure 12 - Comparison of normalised FE data against those obtained using EN 1993 - 1 - 4 for minor-axis FTB of cold-formed angle columns

4. CONCLUSIONS

A comprehensive investigation of the structural behaviour of equal angle columns under pure compression, including experiments (1) and qualitative and quantitative numerical studies (2), was carried out with the aim of acquiring a valuable database that enabled the development of an accurate and reliable design method. The following conclusions were drawn from this investigation:

- For minor-axis flexural buckling, the buckling curve *c* (*α* = 0.49) in conjunction with the non-dimensional limiting slenderness $\bar{\lambda}_0$ = 0.2 may be used for duplex grades for cold-formed equal-leg angle for all cross-section classes.
- The use of buckling curve b (α = 0.34) in conjunction with $\bar{\lambda}_0$ = 0.2 to predict flexural-torsional buckling for duplex grades for cold-formed equal-leg angle leads to safe but quite conservative results characterized by significantly higher scatter.
- For minor-axis flexural buckling, the buckling curve c (α = 0.49) in conjunction with the non-dimensional limiting slenderness $\bar{\lambda}_0$ = 0.2 may be safely used for the design of hot-rolled and laser-welded austenitic stainless steel columns both for non-slender and slender cross-sections.
- The use of buckling curve b (α = 0.34) in conjunction with $\bar{\lambda}_0$ = 0.2 to predict flexural-torsional buckling for the design of hot-rolled and laser-welded austenitic stainless steel columns leads to safe but quite conservative results characterized by significantly higher scatter.

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