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Experimental investigation on flexural behaviour of stainless steel beams

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Abstract

Stainless steel elements have been increasingly used in the construction industry, especially in architectural applications, due to its high corrosion resistance, ease of maintenance and aesthetics. The most important limiting factors restraining structural applications of stainless steel are the lack of knowledge about their resistant properties among designers. This factor has inspired researchers to explore the structural behaviour of the material and develop design rules to exploit this material to its full potential in construction.

This paper aims to present two experimental programmes on stainless steel beams. Information provided by instrumentation in the tests enables us to observe the non-linear behaviour of stainless steel and to reach some useful conclusions for designing stainless steel structures. Experimental results show that current design provisions for this new construction material are clearly conservative.

1 Introduction

Stainless steel is a typical 20th century material. The born of a new material with its excellent aesthetics and ease of maintenance have caused a fast expansion in its use in buildings and civil engineering structures.

Although both carbon and stainless steel design basis are very similar, it is necessary to develop a distinct specification related to stainless steel structures because this material presents clearly different mechanical properties from those of carbon steel. Stress-strain relationship in stainless steel is non-linear even in low stress levels and it presents an important capacity for work hardening. These features affect design rules for the flexural calculations in stainless steel beams. Most of the studies and standards referred to stainless steel are based on rules for carbon steel, which do not consider the effects of the non-linearity in the constitutive equation. Therefore, the resultant design rules have been ridden to a very conservative character. This fact has conditioned the advance of knowledge about stainless steel as a resistant material to be used in metallic construction.

Experimental tests are required to generate data upon which a validated design basis for stainless steel members can be established. This is the aim of this project. Those tests are also needed to develop new design rules, suitable for incorporation into codes enabling stainless steel to be cost-effective used and safety in structures. This study has been performed taking into account the particular features of stainless steel. Part of this work has been focussed on the deflections calculation in order to verify stainless steel structures near service conditions. On the other side, the second part of this program seeks to study the response of stainless steel plated girders subjected to shear load near service conditions and their evolution to failure.

Strain and stress analysis has always been difficult to solve exclusively by the analytical way. In spite of the great advance that numerical methods have supposed to the stress analysis, many problems in practice are advisable to solve by the experimental way. A numerical model in code Abaqus [1] has been used in the different stages in which the study has been divided. This model has allowed us understanding the phenomenon to study, optimising the taking of information during the test and finally, carrying out a comparative analysis of the results.

2 Stainless steel

Stainless steel is the name given to a family of corrosion resistant carbon steels, which contain chromium at 11% or more by weight. Unlike carbon steel, stainless steel has a natural corrosion resistance. The addition of chromium gives resistance properties to the material. This addition allows the formation of a transparent and tightly adherent layer of chromium oxide on the material surface, in the presence of any oxidising environment. If damaged, mechanically or chemically, this film is self-healing providing that oxygen is present. This property makes stainless steel suitable to be used without protection against corrosion, which means considerable savings in initial protection and subsequent maintenance costs during the structure design lifetime. As well as excellent corrosion resistance, stainless steel also displays good mechanical properties and ductility characteristics.

Although the parameters defining the mechanical properties of both carbon and stainless steel are nearly the same, their behaviour is completely different.

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Whereas carbon steel exhibits linear elastic behaviour up to yielding, stainless steel has a more rounded response without well-defined yield stress. The material has a greater capacity for work hardening and the elastic modulus of stainless steel reduces with increasing stress, unlike that of carbon steel. Thus, it is desirable to have an analytical expression for the study and design of stainless steel structural elements. So most of the design guides permit to represent the stress-strain curve by using the Ramberg-Osgood equation:

$$\varepsilon = \frac{\sigma}{E_0} + 0.002 \cdot \left(\frac{\sigma}{f_y} \right)^n \qquad (1)$$

where ε is the strain, σ the stress, E_0 the initial elastic modulus, n a constant related with the non-linearity degree, and f_y (σ_{02}) is the 0.2% proof stress.

3 Experimental tests

3.1 Experimental programme I. Deflections calculation

The main goal of this experimental investigation was to study the flexural behaviour of stainless steel and to obtain the maximum deflection under different load levels, especially near service conditions.

3.1.1 Tested beams: Geometry and material properties

The tested beams in this programme present usual cross-sections in practice. Twelve simply supported and continuous beams with square and rectangular hollow sections and H cross-sections were analysed. The main geometry characteristics and loading schemes of the tested beams are shown in Figure 1.

The single span simply supported beams were subjected to a concentrated load at mid-span and the continuous ones to two concentrated loads close to the mid-span. All the tests were carried out under displacement control. The span length of the analysed beams was designed to an extend enough to reproduce the beam behaviour.

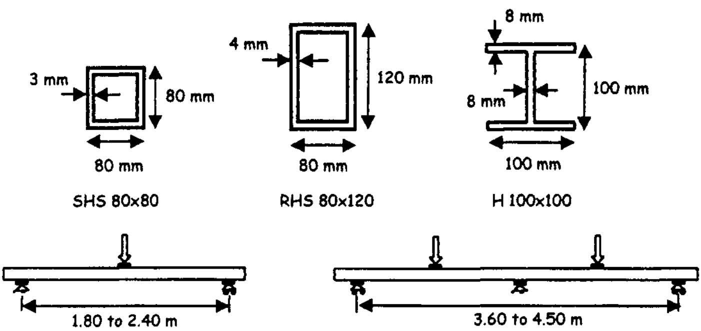

Figure 1: Cross-section and loading schemes of the tested beams

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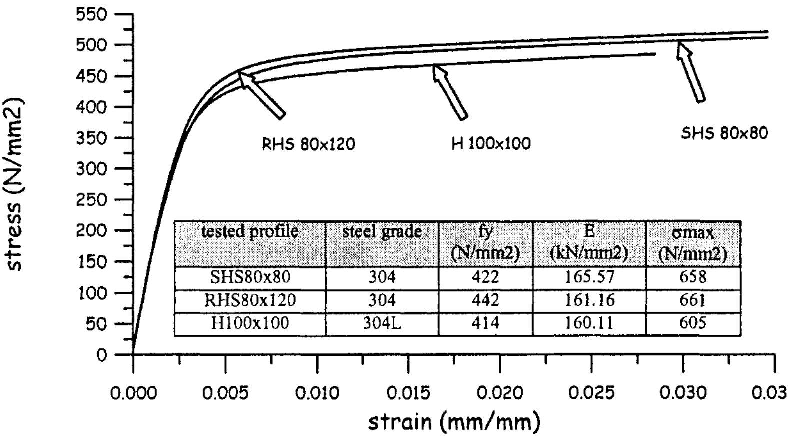
In order to compare experimental results to those derived from the numerical analysis and other analytical formulations is important to know material properties of the tested beams. So, the steel producer tested on the specimens extracted from the profiles, according to ASTM [2], whose results are presented and drawn in Figure 2.



tested profile	steel grade	fy (N/mm2)	E (kN/mm2)	σmax (N/mm2)
SHS80x80	304	422	165.57	658
RHS80x120	304	442	161.16	661
H100x100	304L	414	160.11	605

Figure 2: Material tests results

It may be appreciated that differences between the values of the mechanical properties obtained from the material tests and the ones proposed by Eurocode 3, Part 1.4 [3] are significant. As the Young's modulus values obtained by the tests are lower than the values assumed by Eurocode 3, Part 1.4, the experimental value of the yield stress is higher than the one proposed for the annealed material in the design guide.

3.1.2 Instrumentation of the beams

A suitable instrumentation scheme will allow us to know the stress state of the tested beams with sufficient accuracy. This instrumentation consists of a set of linear displacement transducers to measure deflections, and another one of unidirectional strain gauges for the deformation measuring. In addition, load cells are located at the support sections of the continuous beams in order to know the reaction forces to control possible deviations of the jacking force during test. In Figure 3 the two typical instrumentation schemes used in this experimental programme are represented.

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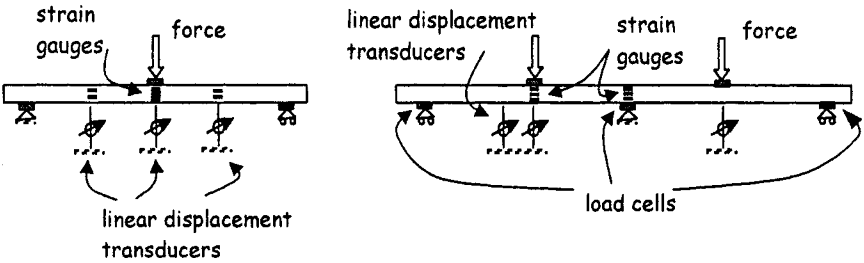

Figure 3: Instrumentation schemes

As it is displayed, three linear displacement transducers were placed in every test. In the first case, one at mid-span under the jacking force, and the others at ¼ cross-sections. In the continuous beams tests one transducer was located at mid-span and the other two were put under the two jacking forces.

It is important to outline that in several cross-sections of the tested beams large deformations of stainless steel were expected. For this reason, it was necessary to use strain gauges with large elongation capacity. In the picture shown in Figure 4 there is a view of one of the tests (continuous steel beam SHS 80x80) where it is possible to see the loading scheme.

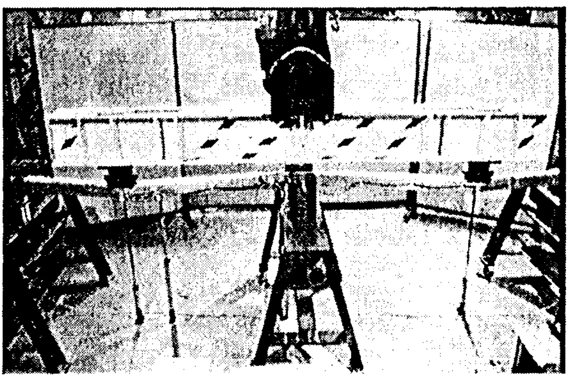

Figure 4: General view of a continuous beam test

3.1.3 Experimental results

Experimental deflections were determined by using linear displacement transducers in all tested stainless beams. Figure 5.a shows the experimental load-deflection curves obtained with the transducers 1 and 3 (ldt1 and ldt3) located at ¼ cross-sections, and with the transducer 2 (ldt2) located at mid-span for the SHS 80x80 simply supported beam.

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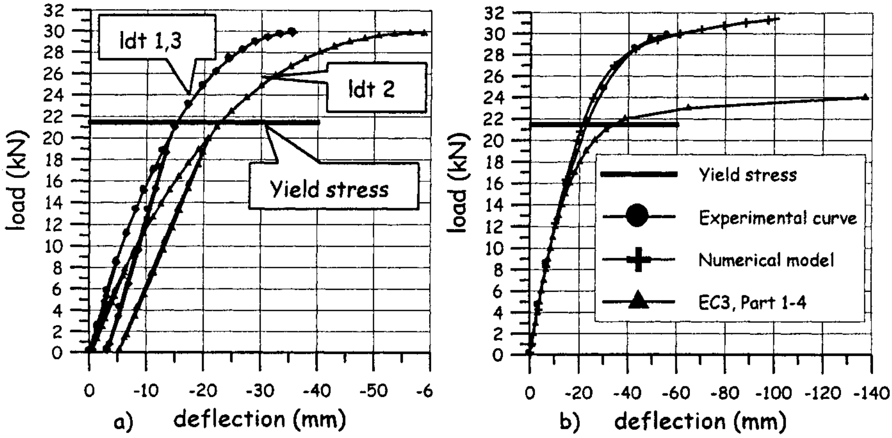

Figure 5: Load-deflection curves for the SHS 80x80 simply supported beam

Deflections obtained by the experimental tests have been compared to those estimated using the method proposed in Eurocode 3, Part 1.4 and the deflections obtained by using code Abaqu (Figure 5.b). The effects of the non-linear stress-strain curve of the material and the effective cross-section should be considered in estimating deflections in stainless steel beams. Eurocode 3, Part 1.4 proposes to evaluate deflections using the secant modulus of elasticity E, determined taking into account stresses in the member under the load combination for the relevant serviceability limit state. On the other side, the numerical model considers the actual stainless steel constitutive equation provided by the steel manufacturer, which allows considering material non-linearity effects through the analysis.

In Figure 5.b it is noticed that the numerical model results agree with the experimental results. As for the results obtained from Eurocode 3, Part 1.4, it can be pointed out that the load-deflection curve, titled *EC3, Part 1.4* obtained by using the minimum value of the secant modulus of elasticity, is close to the experimental curve until 60% of the load value on which the maximum stress in the beam reaches the yield stress. For upper load levels, differences between two curves grow up because Eurocode 3, Part 1.4 method does not consider the variation of elasticity modulus along the beam and within the cross-section.

More detailed aspects related to this experimental and numerical investigation on deflections calculation in stainless steel structures can be found in Mirambell et al [4] and in Mirambell and Real [5].

3.2 Experimental programme II. Shear resistance

The second experimental program seeks to study the response of stainless steel plated girders near service conditions and their evolution to failure. Specifically,

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the behaviour of twelve plated girders subjected to shear load has been analysed. Four of them reached the shear buckling load level.

3.2.1 Tested beams: Geometry and material properties

The tested girders geometry is directly related to the objective of the experimental programme. Therefore, in order to minimise the flexural effects in front of shear ones, all of them were designed as short span and large depth elements.

beam	L (m)	a (m)	d (m)	t_w (mm)	t_f (mm)	λw
ad1w8	1.0	0.5	0.5	8	20	0.673
ad1w6	1.0	0.5	0.5	6	20	0.932
ad1w4	1.0	0.5	0.5	4	20	1.279
ad15w8	1.5	0.75	0.5	8	20	0.771
ad15w6	1.5	0.75	0.5	6	20	1.068
ad15w4	1.5	0.75	0.5	4	20	1.465
ad2w8	2.0	1.0	0.5	8	20	0.817
ad2w6	2.0	1.0	0.5	6	20	1.131
ad2w4	2.0	1.0	0.5	4	20	1.553
ad05w8	1.0	0.5	1.0	8	30	0.817
ad05w6	1.0	0.5	1.0	6	20	1.131
ad05w4	1.0	0.5	1.0	4	20	1.553

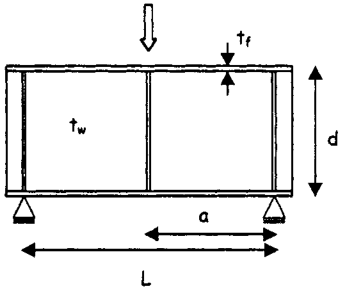


Figure 6: Geometry and load scheme of the tested beams

The twelve beams covered a wide range of web slenderness and several aspect ratios of the web panel that are two determining factors of the element response under shear load. The geometry and main characteristics of the tested beams are presented in Figure 6. As it is also shown in this figure, all of them were tested as simply supported beams subjected to a concentrated load at mid-span.

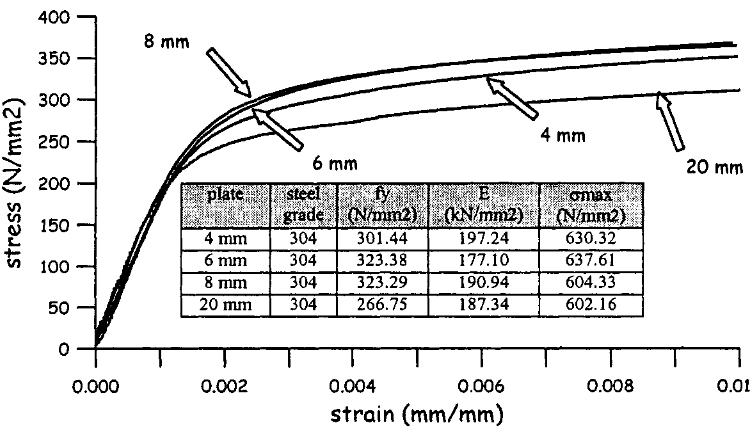


plate	steel grade	fy (N/mm2)	E (kN/mm2)	σmax (N/mm2)
4 mm	304	301.44	197.24	630.32
6 mm	304	323.38	177.10	637.61
8 mm	304	323.29	190.94	604.33
20 mm	304	266.75	187.34	602.16

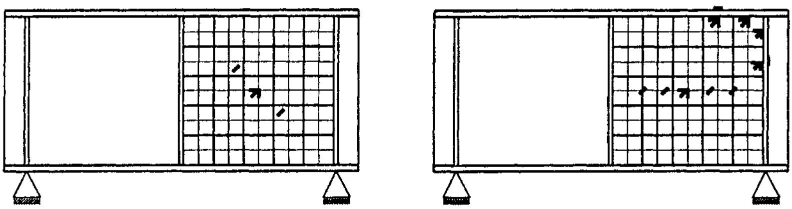
Figure 7: Material test results

As it happened in the first experimental programme, it was necessary to know the actual material properties of the tested elements in order to compare the experimental results to those obtained by the numerical or analytical analysis. The steel producer made tests on the specimens extracted from every type of welded plate used (4, 6, 8 and 20 mm). The results of the material characterisation are presented in Figure 7.

3.2.2 Instrumentation of the beams

Beams instrumentation in this experimental campaign is composed by uniaxial and triaxial strain gauges to measure deformations in web and flanges; and a set of linear displacement transducers to measure displacements.

The instrumentation scheme has been elected after the preliminary stress analysis of the beams with the numerical simulation. From this study, two different responses in front of shear load have been expected. Every one of the instrumentation schemes shown in Figure 8 corresponds to one of both response modes. A group of strain gauges were located on the centre of the web plate in order to evaluate stress levels during the pure shear state and to register the intensity and magnitude of the tension field when it was developed. In the second instrumentation scheme, the strain gauges placed at the corner permitted to know the strain progress in area where the tension field would anchor.



a. Pure shear stress state b. Tension field

Figure 8: Instrumentation schemes

In addition, three displacement transducers were located in the medium high of the plate to register the deformed shape of the web originated during the shear buckling progress. Finally, to evaluate deflections two displacement transducers were placed. The first one was located at the mid-span cross-section and the other one at the bearing section to measure possible bearing displacements.

3.2.3 Experimental results

The two expected response models in front of shear load were confirmed by the experimental results. Beams with 6 and 8 mm web thickness were subjected during all the test to pure shear stress state. On the other side, in those plated girders with 4 mm web thickness shear buckling load level was reached starting to develop the tension field resistant mechanism.

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As to analyse the response of every beam the load-deflection curve is studied. In this curve, it is possible to analyse the main changes in the behaviour of the beam. The experimental curve is obtained subtracting the bearing displacements to the mid-span transducer register. Moreover, this experimental curve is compared with that obtained by the numerical model (see Figure 9). The load-deflection curve in Figure 9 corresponds to a tested beam that has not reached the shear buckling load level.

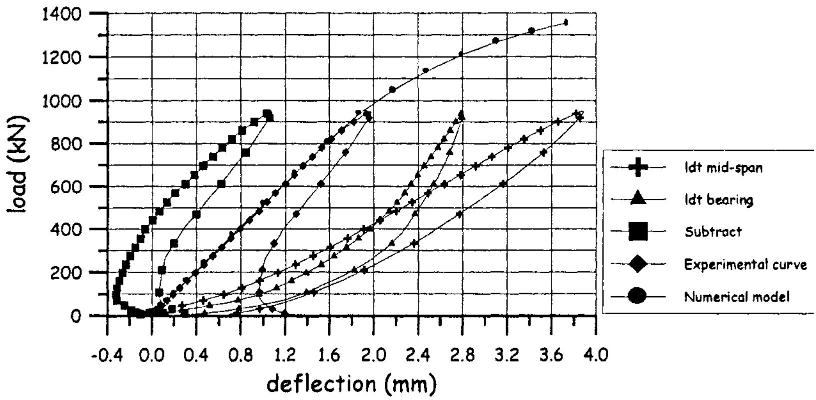
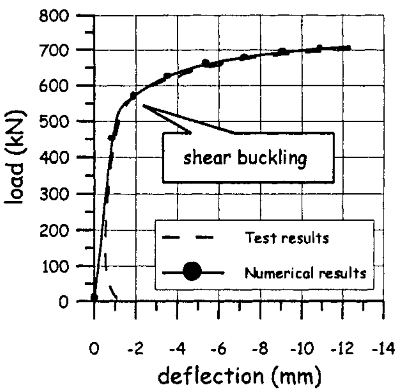


Figure 9: Load-deflection curve in ad15w8 beam test

Figure 10 owns to a plated girder that has suffered shear buckling as it is seen in the important change in the tendency of the curve. A picture of the maximum deformation reached in ad2w4 test is also shown.



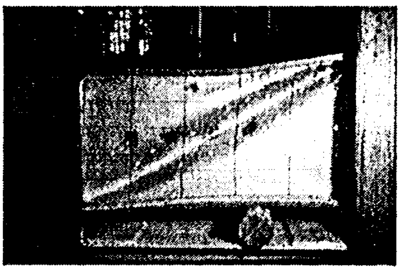


Figure 10: Load-deflection curve in ad1w4 test. Maximum deformation (ad2w4)

Once the general behaviour of the beam is known by the load-deflection curve, it is necessary to start a deeper analysis of the problem, which means an stress study. We are in front of an structural element subjected to a biaxial stress state

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and in presence of a non-linear material. Due to these facts, transforming the strains registered during the tests to stresses is not possible in a direct way. Therefore, the numerical model is used to compare both experimental and numerical results in main strains terms. So, once the numerical model has been validated, it can be used to study the phenomenon in stress terms. In Real et al [6] more detailed aspects related to this experimental investigation on shear resistance can be found.

4 Conclusions

Experimental results obtained from tests allows us reaching some conclusions related to the behaviour of stainless steel structures. On the one hand, from the deflections study it has been demonstrated that the application of the simplified method derived from Eurocode 3, Part 1.4, that considers only one value of the secant modulus of elasticity along the structural element, may lead to overestimate deflections. On the other hand, in the second experimental programme it has been confirmed that stainless steel plates behaviour under shear load is analogue at the one of carbon steel plates. It means the development of the tension field as a new resistant mechanism after reaching the shear buckling load level but clearly influenced by the material non-linearity.

From the comparative analysis of numerical and experimental results it can be concluded that the numerical model provides a good approximation to the actual behaviour of stainless steel structural elements. Therefore, it can be used as useful analysis tool in order to develop and establish new design rules to incorporate into codes.

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