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Residual stress measurements on welded square box sections using steel grades of S235–S960

B. Somodi, B. Kövesdi*

Department of Structural Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3, 1111 Budapest, Hungary

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ABSTRACT

According to the previous research results the effect of residual stresses on the high strength steel members (HSS–S500 and higher steel grades) are less severe than for normal strength steel (NSS –steel grades of S235–S460) structures. Residual stresses have a significant influence on the global stability behaviour of steel structures, therefore the application of the existing buckling curves developed for NSS structures might lead to uneconomic design for HSS structures. To investigate the residual stress distribution in HSS members residual stress measurements are carried out on welded square box sections. The test specimens are delivered by three different manufacturers using seven different steel grades (S235, S355, S420, S460, S500, S960). Based on the test results the shape and the intensity of the measured longitudinal residual stresses are determined and evaluated. The measured values of the residual stress patterns are evaluated in the function of the yield strength and the geometrical properties of the test specimens. The measured residual stresses are compared to the results of the previous test results and an improved residual stress model is developed based on the previous and the current test results. The developed residual stress model is applicable for welded square box sections having steel grades between S235 and S960.

1. Introduction

Previous research results proved that the effect of the residual stresses on the high strength steel structures (HSS) are less severe than in case of normal strength steel (NSS) structures [1,4,6,7]. Therefore, the general aim of the executed research work is to investigate the residual stress distribution and its extreme values in case of HSS welded square box section members having different steel grades. In the research program two different HSS grades are studied (S500 and S960) and for comparison purposes four NSS grades (S235, S355, S420 and S460) are also investigated using the same section geometries and testing method. The investigation of NSS and HSS grades using the same research strategy ensures the exact identification possibility of the differences in the residual stress distribution of HSS and NSS structures. The effect of the steel grade and the geometrical properties are investigated on the residual stresses and a design residual stress model is developed for the stability design of HSS members. The presented research results are part of the RUOSTE: Rules On High-Strength Steel RFCS Project (RFSR-CT-2012-00036) and the STEELBEAM Hungarian R&D project (No. PIAC_13-1-2013-0160).

There are only a limited number of previous residual stress measurements available in the international literature dealing with HSS members. The applicability of these measurements are limited and the test results are not always in harmony. Although the residual stress models for normal strength steel (NSS) section were extensively investigated in the past and design models were developed, the applicability of these residual stress models are questionable in case of high strength steel structures due to the following three reasons:

- the material properties (typical stress-strain curve) and manufacturing process of HSS sections are different from those one used for NSS (conventional rolling, normalizing rolling, thermo-mechanically rolling or quenching and tempering),
- the extreme values of the residual stress pattern can be lower for HSS members compared to the yield strength (f_y), than for NSS structures,
- the current residual stress models do not take the cross-section geometry into account, however several previous test results show, that the residual stresses strongly depend on the width-to-thickness ratio (b/t) of the cross-section.

The current paper focuses on the residual stress measurements carried out on welded box sections. The aim of the current investigations is to measure the residual stresses, to determine the dependency of

* Corresponding author.
E-mail address: kovesdi.balazs@epito.bme.hu (B. Kövesdi).

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the extreme values (maximum tensile and compressive residual stresses) and the residual stress pattern on the steel grade and on the b/t ratio. Based on the measured test results and the previous measurements found in the international literature a design residual stress model is developed. The objectives of the research program are achieved using the following research strategy:

1. literature review on residual stress measurements made on HSS box sections,
2. evaluation and comparison of the available residual stress measurement methods, introduction of the applied method,
3. residual stress measurements on welded box sections with different b/t ratios and different steel grades (S235, S355, S420, S460, S500 and S960),
4. evaluation and documentation of the test results,
5. design residual stress model development for HSS members.

2. Literature overview

2.1. Manufacturing methods

Welded box sections are widely used in the engineering praxis. Its manufacturing method can be different and several previous investigations showed that the manufacturing process has significant effect on the residual stress distribution and intensity. There are three common manufacturing possibilities as shown in Fig. 1. The 1st manufacturing method results in a double symmetric cross section, with symmetric residual deformations and residual stresses. The cross section type 2 has still a square section, but due to the placement of the welds the cross-section loses its double symmetry. In case of the 3rd manufacturing method the weld is not located at the edge of the connected plates, therefore its residual stress pattern can be significantly different from the previous two versions. The specimens investigated in the current project are produced by the manufacturing type 2, therefore the residual stress patterns of the sides A and C (welded side) can be different from the sides B and D.

The residual stress distribution in the welded structures is quite complex and hard to predict theoretically. The magnitude and distribution of the residual stresses can be affected by the manufacturing process, the welding parameters (current, voltage, total heat input, welding speed) and the different cooling rates, which makes the evaluation of the results more complicated, as shown in [15]. The experimental approach is therefore one of the most reliable way to get real information on the residual stresses. The other possible way would be numerical simulation using finite element analysis. It is known from previous investigations that the measured longitudinal residual stresses are commonly considered from two components. The first one is the membrane residual stress that occurs quasi-uniformly through the wall thickness. This component can be determined as the average of the measured values at the two plate sides (outer and inner sides). The second part is the bending residual stress, which can be defined as the deviation from the mean values [1].

2.2. Previous investigations

There are a relative large number of previous investigations available in the international literature dealing with the residual stress distribution of welded box section members for NSS. But there are only a limited number of previous investigations dealing with HSS square box sections. This section summarizes the previous test results on the residual stress distribution of welded HSS square box sections found in the international literature.

Rasmussen et al. [2] investigated different stub columns made of S650 and S690 steel grades in 1992. The complete research program contained box sections, cruciform and I-sections as well. The aim of the investigation was to evaluate the local buckling resistance of the sections using HSS material. For all the analysed cross sections residual stress measurements and buckling tests were performed to investigate the effect of the material grade on the residual stresses and on the buckling behaviour. Three different box sections were investigated with the same wall thickness (5 mm) using different widths (b = 80, 110 and 140 mm). The maximum compressive stress for each side of the specimens was reported. The average of these residual stresses varied between 11% and 26% of the nominal yield strength depending on the plate width. The test results proved, that the b/t ratio has significant effect on the compressive residual stresses and its average value can be significantly smaller than the usually applied value used for NSS grades.

Ban et al. [3] investigated the residual stresses on six high strength steel (S460) welded box section members. Longitudinal residual stress measurements were executed using sectioning technique around the whole cross section including the weld regions as well. Based on the test results Ban et al. concluded that the compressive residual stress significantly depends on the cross section geometry (wall thickness and width-to-thickness ratio). The results showed at the same time that the thickness (8 and 10 mm) has only negligible influence on the compressive residual stresses, however previous results showed the opposite tendency. To clarify the thickness effect on the residual stresses more detailed analysis was suggested by the authors. Furthermore the maximum tensile residual stresses in the corner zones were found smaller than the yield strength, what is usually equal by the yield strength for NSS members and no clear correlation was identified between the maximum tensile stress and the b/t ratio. Based on the test results Ban et al. proposed two analytical models (a complex and a simplified one) for the residual stress determination. In the proposed simplified model the tensile stresses can be set equal to the yield strength (460 MPa), and the magnitude of the compressive residual stress can be determined by the Eq. (1).

$$\sigma_{rc} = -10 - 1500\frac{1}{b_0/t} - 550\frac{1}{t}, \tag{1}$$

Ban et al. [4] studied the overall buckling behaviour of S960 HSS columns as well. Prior to the tests the residual stresses are investigated on six box section members using sectioning technique. Based on the measurements a residual stress model was developed for S960 material, where the tensile residual stress in the weld zone can be set equal to

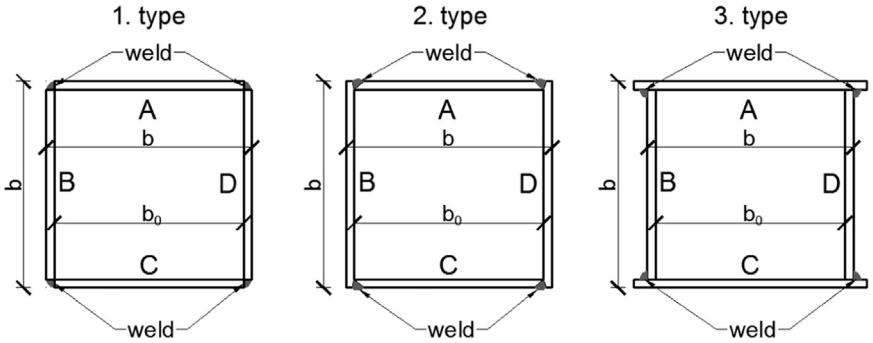

Fig. 1. Manufacturing possibilities of welded square cross sections.