



Flexural buckling resistance of cold-formed HSS hollow section members

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ABSTRACT

The application range of the current EN 1993-1-1 [1] for column buckling resistance determination is limited for steel materials up to the steel grade of S460. The EN 1993-1-12 [2] gives design rules for materials up to steel grade of S700. The stability failure of HSS steel structures is very important in the design, because due to the higher yield strength smaller cross sections can be used, which might be more sensitive for stability failure. According to the previous research results, the global buckling behavior of HSS and NSS columns can be significantly different, however these differences are not considered in the Eurocode based design process. The purpose of the current research is to study the column buckling behavior of HSS cold-formed hollow section columns based on previous and current experimental investigations and based on numerical simulations. This paper focuses on the effect of the different material properties, imperfections and residual stresses on the global buckling behavior of HSS members and to give design proposals for the applicable column buckling curves for steel grades between (S420) S500 and S960.

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1. Introduction

The application field of high strength steel (HSS) is growing currently in the civil engineering praxis due to the numerous advantages of the HSS members compared to the normal strength steel (NSS): economic design, material saving, possibility of creation lighter and more aesthetic structures. However, the application range of the current EN 1993-1-1 [1] for column (flexural) buckling of steel structures is limited to ordinary steel materials up to the grade of S460. The EN 1993-1-12 [2] gives design background for materials up to grade of S700, however, for the determination of the column buckling resistance the same rules are applicable for materials between steel grades S460 and S700 as for the S460 material. However, several previous research results [3–10] prove that the flexural buckling behavior of HSS structures is less severe than in the case of NSS structures.

The difference comes from the different residual stresses, different material properties and geometric imperfections. Many previous investigations and residual stress measurements also prove that the residual stress amplitudes are smaller for HSS structures compared to the yield strength than of NSS members [11–13], which can result in significant benefit in the flexural buckling resistance. On the other hand the reduction due to the flexural buckling is governed by the ratio of residual stress to the yield strength, rather than the magnitude of residual stress itself. Therefore it is expected that a higher column buckling curve could be used for HSS members than for NSS members, consequently the design using HSS structures could be more economical.

The general aim of this research report is to investigate the flexural buckling behavior of HSS columns having cold-formed square hollow sections between S420 and S960 steel grades. Based on the experimental and numerical investigation our aim is to propose a safe and economic design buckling curve for HSS columns.

There are only a limited number of column buckling tests available in the international literature dealing with HSS cold-formed hollow section members. The objective is to collect the available results in the literature for the HSS column buckling test, and to design and perform a new experimental and numerical research program to investigate the global buckling behavior. A total of 45 large-scale tests are carried out in the Structural Laboratory of the Budapest University of Technology and Economics Department of Structural Engineering in 2015. 17 test specimens investigated had steel grades between S500 and S960. In addition to these tests complementary investigations on 28 test specimens are made on S420 and S460 steel grades. The aim of the complementary tests are to give reference and comparison background to the test results made on HSS members (S500–S960) and to increase the investigation range. The test specimens were produced by three different European steel manufacturers.

Parallel to the experimental research program a detailed numerical investigation is also carried out to determine the flexural buckling resistance of HSS hollow section columns and to investigate the differences between NSS and HSS members. In the frame of the numerical investigations the differences in the flexural buckling behavior are investigated, which come from (i) the different yield strength, (ii) the different residual stress pattern and (iii) the different steel material properties (stress – strain diagram). Based on the current and the previous experimental results found in the international literature and based on the

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current numerical investigations the differences in the flexural buckling behavior of HSS and NSS members are identified, studied and evaluated. Finally based on the experimental and numerical investigations design buckling curves are proposed for cold-formed HSS hollow section members.

The presented research results are part of the RUOSTE: Rules On High-Strength Steel RFCS Project (RFSR-CT-2012-00036). Previous research results [12–15] showed that there are significant differences in the residual stress distribution depending on the manufacturing process, which can have dominant effect on the flexural buckling resistance as well. Therefore it has to be mentioned that all the specimens investigated in the current research work are produced by “continuous forming - indirect way from circular to square” manufacturing process. The current investigations are focusing only on the flexural buckling resistance of these product types. The objectives of the research program are achieved by the following research strategy:

1. literature review on buckling tests of hollow section HSS columns,
2. flexural buckling tests on cold-formed HSS members with different global slenderness and different steel grades (S420, S460, S500, S700 and S960),
3. evaluation and documentation of the test results,
4. numerical parametric study to investigate the flexural buckling behavior of HSS structures compared to NSS members,
5. investigation of the differences in the structural behavior coming from the different (i) material properties, (ii) geometric imperfections and (iii) residual stress patterns and magnitudes,
6. proposal for design column buckling curve for cold-formed HSS hollow section members based on present and previous test results and based on the numerical parametric study.

2. Literature overview

2.1. General observations

There are a relative large number of previous investigations available in the international literature dealing with the global (flexural) buckling resistance of hollow section members for NSS. But there are only a limited number of previous investigations dealing with HSS square hollow sections. The following publications listed below are found by the authors dealing with global buckling behavior of HSS hollow section columns:

- 1970 – Nishino and Tall [3];
- 1983 – Fukumoto and Itoh [4];
- 1994 – Rasmussen and Hancock [5];
- 2012 – Pavlovčič, Froschmeier, Kuhlmann and Beg [6];
- 2012 – Ban, Shi, Shi and Wang [7];
- 2013 – Ban, Shi, Shi and Bradford [8];
- 2014 – Wang, Li, Chen and Sun. [9];
- 2014 – Design guidelines of the SSAB [10].

It can be observed from the list, that there are several early publications from 1970 to 1994 investigating the flexural buckling resistance of HSS columns. All the results showed that based on the yield strength, normalized flexural buckling resistance made from HSS are larger compared to specimens manufactured from NSS. The experiments also showed that the flexural buckling phenomenon of the HSS columns are different from the NSS structures, which come from the different residual stress pattern, geometric imperfections (manufacturing quality) and different material properties. Between 2012 and 2014 an intensive research activity was started again in this subject in China, Australia and also in Europe within the RUOSTE: Rules On High-Strength Steel RFCS Project (RFSR-CT-2012-00036). The main goal of these investigations is not only the characterization of the flexural buckling phenomenon for HSS hollow sections, but also the standardization and the selection

of applicable column buckling curves. The investigations made in China are focusing on welded hollow sections, the Ruukki company in Finland investigated only cold-formed hollow section columns, and the current investigation at the BME contains both, welded and cold-formed sections as well. The current paper focuses only on the cold-formed section resistances.

All the previous papers were focusing on a specific new steel material (S420, S460, S690 or S960) and the flexural buckling behavior was characterized for that specific steel grade. The specialty of the current investigation is that it focuses on a range of steel materials (S420, S460, S500; S700 and S960) ensuring the exact comparison possibility, using the same loading machine, same support conditions and the same evaluation process.

2.2. Results of the previous investigations on cold-formed members

The main part of the previous investigations were focusing on the flexural buckling behavior of welded HSS members, and there are a very limited number of available investigations made on HSS cold-formed sections.

Four buckling tests were executed on centrally loaded RHS sections by Pavlovčič et al. in 2011 [6]. Two welded and two cold-formed section specimens were tested in the experimental research program with 4000 mm and 5200 mm column lengths. The welded cross section has been manufactured by welding at the corners and the cold-formed specimens were welded from two cold-formed U-sections. The average yield stress of the specimens was 373.4 MPa, which does not belong to the range of the ultra-high strength steel, but the investigations give good reference points to the results achieved on HSS structures. The research work combined experimental and numerical studies. From the 8 full scale tests 4 specimens were loaded by pure compression and 4 by combination of compression and bending, by varying the loading eccentricity. The specimens were tested between pinned end conditions, the shorter specimens failed by interaction between local and flexural buckling, the longer ones by flexural buckling. Based on the experimental and numerical investigations the authors concluded that the residual stresses have significant impact on the column buckling resistance, which can reduce the column buckling resistance up to 37%. In the case of centric tests the complete imperfection combination reduces the resistance up to 45% regarding the initially perfect column. With the increase of the designed load eccentricity the imperfections have smaller influence (reduction by 11–19%), since the load eccentricity reduces the column resistance already. From the tests they concluded that it is unavoidable to implement different geometric imperfections based on real test data and measurements. Based on the verified numerical model a numerical parametric study has been completed to investigate the relevant equivalent geometric imperfections which represent the real structural behavior of the structures studied in the tests. The numerical calculations showed that the measured geometric imperfections and residual stresses may be suitably replaced by equivalent geometric imperfections with amplitudes according to the recommendations of the EN1993-1-1 [1] and EN1993-1-5 [16].

Design guide development was made by SSAB steel company in cooperation with the Tampere University of Technology [10]. In this study the flexural buckling resistance of the double grade (S355, S420) steel hollow sections manufactured by SSAB was studied. Double steel grade means that the material fulfils the requirements of the S355J2H and S420MH materials. Only cold-formed specimens are investigated in the experimental research program, which are statistically evaluated and based on the test results an applicable design buckling curve and the corresponding partial safety factor is proposed. A total of 39 cold-formed hollow section specimens were tested under axial loading at the Lulea University of Technology during 2014. The failure mode of all the specimens was global buckling without any local buckling problems. The investigated cross sections have the following dimensions: 50 × 50 × 2; 100 × 100 × 3; 150 × 150 × 5; 200 × 200 × 6; and

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