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Resistance of cold-formed built-up stainless steel columns – Part II: Numerical simulation

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ABSTRACT

In parallel with an experimental investigation of the flexural buckling behaviour of built-up stainless steel columns presented in the accompanying paper (Dobrić et al., submitted for publication), a detailed Finite Element Analysis (FEA) has been performed to simulate the experiment and identify the key factors affecting the buckling response. The FEA entailed realistic geometry, measured geometric imperfections and material properties of the specimens. Very good agreement was obtained between the experiment and FEA, which proved the capability of the computational approach to replicate experimental results and predict ultimate buckling loads. In the absence of explicit design rules for flexural buckling resistance of stainless steel closely spaced built-up members, the experimental results were compared with design predictions according to the existing European Standard and American Specification for carbon steel structures. The findings indicate that the mentioned design standards may be very conservative regarding the buckling resistance of stainless steel built-up members; this under-prediction may be associated with the impact assessment of chord slenderness and interconnection stiffness on the buckling response. The main purpose of this research is to establish a qualitative data base reliable for the further quantitative numerical parameter analysis and for the development of new design rules for compressed stainless steel cold-formed built-up members.

1. Introduction

The cost of structural stainless steel elements is increasingly important in a competitive construction market. Closely spaced built-up members may provide relatively light structures which have very good overall performance under compression loads. This type of structural element is often made from two parallel individual chord members discontinuously interconnected by bolts or welds. The chord members are usually channels or angles which may be in direct contact or closely spaced and interconnected through packing plates. The most popular structural configuration is to arrange the chords back-to-back, essentially forming an open section. The proper position of individual chords within the built-up section is strongly associated with the magnitude of the cross-section's second moment of area and consequently with the beneficial structural effectiveness of various compressed elements. The main goal of the research presented in this and an accompanying paper [1] is to improve the competitiveness of stainless steel members in civil structural applications. The research is intended to cover an experimental and numerical work with the aim of acquiring further knowledge that will facilitate the development of design rules for closely spaced built-up stainless steel columns. The investigation was concentrated on the most commonly used austenitic stainless steel grade EN 1.4301 (X5CrNi18-10). The research activities focused on pin-ended centrically compressed built-up members formed from two press-braked channel chords, directly interconnected and oriented back-to-back. The sizes of the built-up sections were selected so that the tested columns had a semi-compact ultimate response, in order to avoid the reduction of compressive member capacity by elastic local buckling. Discontinuous welds between the individual chord members were investigated in order to reduce the cost and minimize the sections' distortions usually caused by continuous welding in the production process. In addition, the behaviour of the welded built-up columns is compared with the columns having individual chords discontinuously connected by means of bolts at the webs. The series of flexural buckling tests of closely spaced built-up stainless steel columns about their minor structural axis were performed and presented in [1].

This paper focuses on the numerical procedures employed for the simulation of the structural responses of the built-up specimens used in the experiment [1]. A quasi-static analysis was made with the Abaqus software package [2] employing its explicit dynamic solver, which is suitable for simulating the quasi-static buckling response by properly using the mass-scaling technique. The developed Finite Element (FE) models were calibrated and validated by

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experimental results provided in the accompanying papers [1,3]. The analysis was intended for the study of structural properties of tested specimens: material nonlinearity, strain hardening effects, imperfections caused by the manufacturing process, stiffness of interconnections and contact conditions between individual chords of built-up section. In addition, the conducted experimental procedure that included the testing of specimens with "knife edge" ends was verified through a critical comparison of ultimate buckling loads between FE models which reflect the real tested specimens and equivalent FE models with theoretically "exact" pin-ended boundary conditions. Consequently, the conjecture that the effective buckling length of tested specimens is equal to the distance between their end cross-sections is confirmed. By accomplishing an agreement between experimental and numerical results, the preconditions for comparisons of the experimental data [1] with design predictions determined according to existing European [4,5] and American design codes [6,7] both for carbon steel and stainless steel, are met.

2. Description of the FE modelling

2.1. Analyses methods

Two types of numerical analyses were performed for each FE model: eigenvalue buckling analysis and nonlinear buckling analysis. The eigenvalue Linear Buckling Analysis (LBA) was employed as a means of estimating critical buckling mode shapes and obtaining initial geometric imperfections of structural geometry in order to permit a realistic incremental nonlinear FEA. Several solution methods are available in Abaqus [2] for modelling nonlinear static problems of members that include buckling behaviour. Among them, the Riks method or arc-length method, presents the fundamental procedure. The only requirement for the utilization of the Riks method is that the equilibrium path in load–deformation must be continuous or reasonably smooth and without branching. The assessment of numerical accuracy of the ultimate load depends on the magnitude of initial geometric imperfections of a real structural element. The real slender element with negligibly small initial imperfections may reach the ultimate load that is slightly different from critical load; the initial part of the equilibrium path is steep upward and after reaching the point of maximum load, lateral deformations of the element suddenly increase. In such cases, implementation of the modified Riks method may lead to divergence of the solution. Additionally, this method has a restriction in analysis of complex structural elements whose behaviour is followed by large deformations or by separation of contact surfaces between individual integrated members. For evaluating the solution, a quasi-static, explicit dynamic analysis is often used. However, the application of explicit dynamics to analyse quasi-static problems leads to the impractical duration of the computational process in real time. In order to obtain economical quasi-static solutions, calculation speed can be increased by using time scaling or mass scaling techniques. Consequently, inertial forces can become more dominant. Hence, the process should be modelled in an acceptable time period in which the dynamic effects would be insignificant and deviations of the obtained results in comparison with the static solution would not be considerable. This can be achieved through gradually loading the FE model by defining a smooth load–time amplitude function.

In this framework, a geometric and material nonlinear analysis was performed as quasi-static with the dynamic explicit solver because it does not have usual convergence issues as the modified Riks method does. The option of mass scaling was used with the target time increment of $\Delta t = 1 \times 10^{-5}$ s. Preliminary computations were made in order to select the appropriate target time increment. Scaling was set to be variable and non-uniform. An appropriate smooth curve was adopted for amplitude functions in all loading steps to avoid large inertial forces in the quasi-static analysis.

2.2. Geometry, boundary conditions and mesh

Two types of FE models which represented the specimens with welded and bolted interconnections are shown in detail in Fig. 1. Taking into account that there are no significant differences between nominal and measured geometrical dimensions of the tested columns [1], the FE models were built by using their nominal geometry. The chords were modelled as S4R shell elements with reduced integration. Mesh sensitivity study was performed with sizes 3 mm, 6 mm and 12 mm and finally 6 mm was chosen providing almost same results as 3 mm mesh size at much less costs in computation time. The hexahedral solid elements C3D8R, 6 × 6 mm in size, were used to form the mesh of the welded interconnections.

Modelling of the bolted interconnections is a very important issue regarding the simulation of effects of slip between the individual chords. The attachment tool in the Abaqus software package [2] which involves attachment points was utilized to model the bolts in a nominal arrangement between chords. A single attachment point was considered for each bolt. The bolts were modelled using the "Cartesian" mesh-independent connector type. Linear elastic behaviour was assumed for the connection without consideration of rotational stiffness. Linear elastic stiffness was calibrated to a value of 50,000 N/mm, on the basis of experimentally gained structural response of all tested specimens with bolted interconnections in the whole loading range. The degrees of freedom of the bolt were coupled to the adjacent nodes by distributing coupling between the connector point and its corresponding surface on the chord's web. The corresponding nodes on the chords' webs within the radius of 5 mm around the reference point are kinematically constrained by means of two rigid bodies connected by a spring element.

The shape and dimensions of the FE models' ends correspond to real geometry of the "knife edge" ends of tested specimens (see Fig. 2). In order to simulate equivalent Boundary Conditions (BCs) at the ends of the models, the end plates of the testing machine were modelled as a 2D rigid body. Two reference points named "Jack" and "Support" (see Fig. 1) were set at the centroid of the top and bottom bearing plate. Failure loading was applied as displacement controlled. A vertical displacement of U3 = 10 mm was applied to the top reference point.

Contact conditions between the chords and the welds were defined by tie constraints at the joining surfaces. The surface-to-surface general contact interaction was selected as the modelling approach, to take into account the interactions between individual chords, and also between the end cross-sections of FE models and bearing plates. The "hard contact" formulation of normal behaviour and the "penalty friction" formulation of tangential behaviour were used. The friction coefficient of 0.35 was assumed for all contact surfaces as no special treatment was applied.

The designations of the FE models are in accordance with the labelling system of tested specimens as explained in accompanying article [1]: the first letter indicates the shape of the chords' cross-section – U, the subsequent number indicates the overall slenderness of the column about its minor axis, and the final letter *b* or *w* indicates the interconnection type, bolted or welded, respectively. The number in the third position represents the number of modules between the interconnections. An exception from this rule is the label of the column with a solid cross-section formed by continuous welding of chords, U92w-1.

2.3. Material modelling

In the FE models, material properties obtained from the flat and corner longitudinal tensile coupon tests [3] were assigned to the flat and corner parts of the press-braked chord section. The material strength of the corner parts was confined to the corner region, finding that there are not significant strength increases beyond the curved portions. The material properties of the flat parts are similar as those of the