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Local buckling behaviour of thin-walled members with curved cross-section parts

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ABSTRACT

In this paper the buckling behaviour of thin-walled members with cross-sections with curved parts is investigated. Due to the curved parts, shell-like buckling is a potential mode of failure. The objective of the research is to understand whether shell-like buckling behaviour might be governing in practical cold-formed steel members. For this aim, numerical studies have been carried out, involving linear buckling analysis as well as nonlinear shell finite element analysis with imperfections, by considering a large number of various cross-sections. Standardized capacity prediction has also been completed, based on elastic critical loads by using the direct strength method, and the results have been compared to that of shell finite element analyses. Based on the results it is concluded that shell-like behaviour might be critical in certain cases, but only in case of unusual cross-section geometries. It was also found that the simple direct strength capacity prediction can reasonably be used in most of the cases.

1. Introduction

As linear cold-formed steel profiles have become everyday solutions in many applications (e.g., purlins, rafters), several research activities started with aiming to develop more efficient cross-sections. These research and/or innovation activities led to more refined cross-section shapes, e.g. with multiple longitudinal stiffeners. Lately, attempts for a more formal mathematical optimization have been reported by various research groups, see e.g. [1–10]. Though these research activities are different in many aspects (e.g., different objective functions are used, different optimization techniques are used, different topologies are considered, etc.), still they share a few important common features. First, practically all of them use the Direct Strength Method (DSM) [11] for capacity prediction, which, at least formally, can be applied to virtually any cross-section geometries, even if its safe applicability has been proved for only certain (so-called pre-qualified) cross-sections. Another common feature is that the found optimal cross-section shapes tend to consist of curved parts rather than flat parts, at least if no special constraints are used to avoid the formation of curved parts. Though from a different root (namely: trying to improve seismic capacity of thin-walled sections for moment resisting frames) and without formal mathematical optimization, researches in [12,13] also concluded that cold-formed lipped channel sections with curved flanges are superior to the classic flat-flange C sections.

Obviously, the highly curved cross-section shapes might be impractical. That is why many of the above-mentioned research groups provided optimal shapes also with considering some production and/or construction constraints, preventing or only partially allowing the formation of curved parts in the optimized cross-section. Based on all these results, it is reasonable to assume that some combination of flat and curved parts might be feasible and advantageous, e.g., by assuming some classical cross-section, but with unusually large corner radii.

The problem is, however, that the behaviour of thin-walled members with curved cross-section parts is not yet investigated in a comprehensive manner, therefore it is questionable whether the reported optimal cross-sections are properly analysed by considering all possible failure modes. Two potential problems might be mentioned. First, it is questionable whether DSM can properly be used to predict the design capacity of cross-sections with curved parts. Second, since curved cross-section parts mean cylindrical surfaces, shell-like behaviour is theoretically possible, but shell-like behaviour is certainly not considered by DSM (and in fact by any current design procedure for cold-formed steel members). This second question might be especially important. Though plate-like and shell-like buckling are geometrically similar, both being associated with small buckling waves, they might have significantly different post-buckling behaviour: plate-like buckling has typically considerable post-buckling reserve (i.e., the load-bearing capacity might be considerably above the critical load), in case of shell-like behaviour, however, the capacity is typically much smaller than the critical load. Therefore, if shell-like behaviour is physically possible but

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not considered by the design procedure, the design might be highly unsafe and the so-optimized cross-sections might not be optimal.

Since according to the knowledge of the authors this problem has not yet been addressed, a small research program has been completed to get a basic understanding (i) whether cross-sections with curved parts can be analysed by DSM, and (ii) whether shell-like failure of cold-formed steel members is a failure mode to be considered. Based on the results we might also have basic knowledge whether cold-formed steel members with curved parts can be beneficial to use, compared to typical quasi-sharp cornered cross-sections. Some preliminary results of this research program have been reported in [14,15], while in this paper the whole research program is briefly summarized.

First the numerical studies are presented, completed by shell finite element analysis. Both column and beam members are investigated, considering two cross-section topologies, but a large number of curved and non-curved cross-sections, by systematically changing the corner radii in a wide range. Linear buckling analysis (Section 3), as well as geometrically nonlinear analysis (Section 4) and geometrically and materially nonlinear analysis with imperfections are presented (Section 5). The results are evaluated in the light of some current design procedure, namely Eurocode 3 [16–18] and the direct strength method of the North American Specification (NAS) for cold formed steel structural members [19] (Section 6). Finally, based on the completed calculations and comparisons conclusions are drawn.

2. Overview of the completed research

2.1. Overview

The objective of the research is to check whether shell-like buckling can or cannot be governing in case of thin-walled cold-formed steel column and beam members. In other words, we want to check whether the presence of curved parts in the cross-section geometry deteriorates the post-buckling reserve of the buckling (i.e., buckling characterized by small waves). The aim is not to investigate specific products, but to analyse the phenomena. Therefore, only simple cross-section geometries are selected. One single cross-section topology is chosen for pure compression, and another one for pure bending. The topology for compression is a doubly-symmetrical hollow section shape, (with a maximum dimension of 100 mm,) while the topology for bending is a C-like singly-symmetrical open cross-section shape (with 100 mm width and 130 mm height). It is to note that this slightly unusual lipped-channel geometry is selected in order to eliminate distortional buckling and to be able to investigate cross-sections with very large corner radii. Also, in most of the cases this geometry prevents the plate buckling of the lip, though this phenomenon is not totally excluded. Since the emphasis is on the curved parts, within the given topology, the corners are rounded with variable corner radius, the radius varying in between zero (i.e., sharp corners) and the physically possible maximum (i.e., 50 mm). In case of the hollow section, therefore, the increasing radius transforms the shape from a square hollow section (SHS) to a circular hollow section (CHS), as shown in Fig. 1. The figure shows the considered C-like shapes with the changing corner radius, too.

Since the aim here is to analyse buckling with short buckling waves, only short members are considered, with a length equal to 200 or 300 mm, i.e., the length is roughly twice as much as the maximum cross-section dimension. The selection of short member length automatically eliminates the global buckling phenomena. The distortional buckling is not fully eliminated, still, the short member length and the selected cross-section shapes reduce its significance. In case of hollow sections distortional buckling mode theoretically exists, however, the associated critical load is much larger than those belong to local-plate buckling, hence, it is reasonable to assume that the effect of distortional buckling for the considered column problems is negligible. In case of a C-like cross-section distortional buckling is typically important, however, in our cases the flange lips are relatively large, and if such a cross-section is subject to bending, the lips are lightly compressed, hence it is reasonable to assume that distortional buckling and/or lip buckling has minor role.

The final goal of the numerical studies is to estimate the load-bearing capacity of the members with (and without) significant curved parts and then to make a comparison to existing design procedures. In the lack of real experiments, the load bearing estimation is carried out by finite element analysis, using shell finite elements, considering material and geometric nonlinearity with imperfections (i.e. GMNI analysis). Equivalent geometric imperfections are used, taken as properly scaled buckling shapes.

The major steps of the research work are as follows:

- parametric model definition,
- linear buckling analysis for a large number of cases, by systematically changing the model parameters in wide range of the parameters,
- development of a method to numerically and automatically characterize the buckling modes,
- imperfection sensitivity analyses by using elastic material and geometric nonlinear analysis with geometric imperfections (i.e., GNI analysis),
- load bearing capacity estimation with geometrically and materially nonlinear analysis (i.e., GMNI analysis),
- evaluation of the GMNI capacity prediction in the light of direct strength method (DSM) and the Eurocode 3 design procedure.

Based on the results some qualitative and (approximate) quantitative conclusions can be drawn.

2.2. Parametric FE model

For the parametric studies a parametric finite element model was built in Ansys [20]. The geometry of the analysed cross-section topologies is illustrated in Fig. 1. Eight-node quadratic shell elements have been used, with six degrees of freedom at each node. This element is called SHELL281 in Ansys terminology. A relatively fine mesh is used, the total degrees of freedom being approx. 34,000–47,000 in case of the SHS-like sections and 51,000–98,000 in the C-like sections. The size of the equation system was a key factor since thousands of cases have been investigated, therefore, a balance had to be kept in between accuracy and running time. It is to mention that some other finite element types have been tested, too, but it was concluded that there is no significant difference in the results if appropriate mesh density is chosen.

A globally and locally hinged support was defined for both end sections. Warping is practically restrained. One may think of this support arrangement as if thick plates were welded to the end cross-sections, and the plate is supported in one point by a hinge (i.e. by restraining translations and twisting rotation around the longitudinal axis of the member, while allowing the rotations around the other axes). Practically, a master node is defined at each end to which each end cross-section node is linked by rigid constraint equations. It is to note that some slightly different support arrangements were also considered, but it was concluded that it had no any significant influence on the local behaviour.

3. Linear buckling analysis

3.1. Results

Linear buckling analyses are performed for both cross-section topologies, with varying corner radius and thickness. More specifically, the thickness varied from 0.4 mm to 1.0 mm by 0.1 mm steps and from 1.0 mm to 3.0 mm by 0.2 mm steps, while the corner radius varied from zero to the physically possible maximum 50 mm by 5 mm steps. Altogether 685 cases are analysed, and in each case the first 200–300