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Probabilistic estimation of the buckling strength of a CFS lipped-channel section with *Type 1* imperfection

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ABSTRACT

Local geometric imperfections in a cold-formed steel (CFS) member can significantly alter the force-carrying capacity of the member. These are the dents and undulations which occur during cold-rolling, handling, transportation and erection of CFS members. The buckling strength of a lipped channel section with *Type 1* local imperfection is obtained and characterised statistically using finite element analyses and Monte Carlo simulations. The reduction in strength due to these imperfections are found to be significant. The quantification of reduction in strength due to these imperfections is found for different values of non-dimensional slenderness ratio. Based on the statistical analysis, design equations and strength curves are recommended for the buckling strength of geometrically imperfect members. Legitimacy of using a generalised statistics of imperfection, in the case of unavailability of specific data for a particular section, is also verified.

1. Geometric imperfections in cold-formed steel sections

Cold-formed steel (CFS) sections are fabricated from thin steel sheets using either press-braking or roll-forming process, by passing the sheet through a number of dies. The characteristic that differentiates CFS sections from hot-rolled ‘structural’ steel sections is that the shape of the cross-section, instead of the thickness of the section, is used for carrying loads [1]. The force carrying capacity of CFS sections depends largely on the shape achieved through a cold-forming process. Deviations from the target shape may affect a CFS section's capacity significantly. However, due to a multiplicity of reasons it is almost impossible to maintain the perfection in the cross-sectional dimensions of a CFS section that is finally used in construction. One major reason is that cold-rolling mills do not adhere to a very strict quality in the cold-rolling process, which results in geometrically imperfect sections coming out of these mills. The other significant reason is the loads during handling, transportation, and erection (those loads, for which the section is not typically designed), which cause visible deformations in these thin members. Geometric imperfections (GIs) in CFS sections include global and local deviations. Whereas global behaviours, such as bow, camber and twist, are categorised under global GI, local deviations are characterised by dents and undulations in the member elements (flange, web etc.). As mentioned earlier, these deviations can significantly alter the force-carrying capacity of a section.

CFS sections are characterised by the presence of different instability modes, such as local, distortional and global buckling, prior to the ultimate ‘failure’ of the member. The design of these sections is generally governed by the ‘post-(local/distortional) buckling’ behaviour. The strength limit states are defined by ‘overall’ buckling, which includes *flexural*, *torsional* and *torsional-flexural* modes. Owing to typical proportions of CFS member elements, these buckling modes (in real structures) are usually elastic [2]. However, some stocky members fail by inelastic (overall) buckling as well. Design standards, such as AISI S100 [3] or AS/NZS 4600 [4], include the effect of inelasticity in the post-(local) buckling behaviour of CFS members. In this article, we focus on the effects of *Type 1* local geometric imperfections on the buckling strength of a lipped channel (‘C’) section, in a statistical sense. A lipped C section is considered for this study because these are the most commonly used sections in structures made of cold-formed steel, other than ‘Z’ sections.

2. Previous studies on geometric imperfections in CFS sections

A local (or, cross-sectional) GI is understood as local unevenness or undulation in the elements of cross-section distributed over the length of the member, which is generally referred as local geometric imperfection or cross-sectional geometric imperfection [5]. Schafer and Peköz [6] categorised the local GIs into two groups:

1. *Type 1*: Maximum local imperfection in a stiffened element, such as a web

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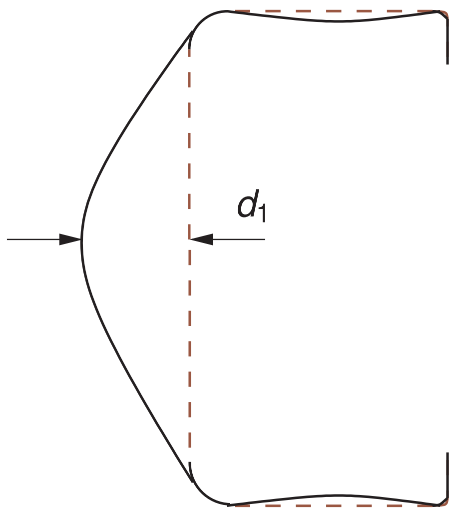

Fig. 1. *Type 1* geometric imperfection of the lipped channel cross-section.

2. *Type 2*: Maximum deviation from straightness for a lip-stiffened or an unstiffened flange

Fig. 1 illustrates the *Type 1* deformation for the case of a lipped channel section. The local deviations are characterised by 'dents' and 'irregular undulations' in the plate. However, they found that little or no information was available on the specific location of these dents, which made it difficult to find which eigenmode(s) a specific imperfection would trigger. In their detailed statistical treatment of geometric imperfections based on the collected data, Schafer and Peköz [6] considered the amplitude of the imperfection as a random variable, and recommended a direct probabilistic simulation of both the imperfection magnitude and its distribution along the length of the member as the most robust way to assess the effect of geometric imperfections. However, they also pointed to the difficulty with the practical implementation of such an approach, and suggested more affordable but less accurate approaches.

Traditionally, the effective width method [3] has been used to evaluate the strength of the CFS member. This method includes the effect of local buckling [2], but not the effect of interaction of different elements of a cross-section [7,8]. In addition, this method is very tedious. The semi-empirical approach adopted from Winter [9], which is a modification of the theoretical equation originally proposed by Karman et al. [10], does not explicitly account for geometric imperfections, either. However, since the modification of Karman et al. [10]'s equation was based on experimental results of real sections, one can expect that the equation(s) in AISI S100 can somewhat represent the imperfection, although not rigorously but in a very limited manner. However, as highlighted before, local geometric imperfections are very random in nature [6,11]. Therefore, a rigorous treatment of this randomness is necessary for a proper assessment of a CFS column's load carrying capacity.

In this line, many researchers measured and characterised geometric imperfections in CFS sections [6] and tried to quantify their effect(s) on the capacity of a CFS member. Young and Rasmussen [12] performed compressive tests on two cross-sections of lipped channels, with two different boundary conditions. Prior to the test, detailed measurement of geometric imperfections was performed and reported. Dubina and Ungureanu [13] studied the effect of geometric imperfections on the buckling strength of CFS channels through numerical simulations. They pointed out the necessity of the codification of both size and shape of imperfections for numerical analysis. Also on the basis of their study, they showed that the different shapes of local imperfection have different effects on the buckling strength of the member. The importance of the selection of an initial geometrical imperfection magnitude in nonlinear FE analyses of CFS was presented by Bonada et al. [14]. Loughlan et al. [15] examined the failure mechanism of fixed-ended CFS lipped channels with due consideration to the influence of geometric imperfections. Results from the finite element simulations compared favourably with the tests performed, when the local geometric imperfection was properly modelled. They also reported the substantial influence of geometric imperfection on the load-deformation and buckling behaviour from the onset of loading. Dinis et al. [16] analysed the coupled instabilities in CFS lipped channel columns through finite element analyses. They showed the influence of GI on the elastic-plastic post-buckling behaviour of fixed-ended lipped channel columns. They also found the strength estimations based on the direct strength method (DSM) to be inaccurate for these cases.

So far, research on the effect of GI on the behaviour of CFS sections primarily looked at aspects such as numerical modelling of GI, selection of GI, impact of model interaction, etc. However, very little work has been reported on the probabilistic performance assessment of the CFS member with geometric imperfections. Considering this fact the main focus of this work is set on the probabilistic estimation of buckling strength of a CFS member with local geometric imperfection.

3. Objective and scope of the work

The primary objectives of this work are (i) to find the effect of *Type 1* local geometric imperfections on the buckling strength of a CFS section, (ii) to statistically quantify this strength, and (iii) to compare the findings with the recommendations given in design codes (which do not explicitly account for such imperfection effects). Due to the presence of uncertainty in local imperfection magnitudes, a probabilistic framework is preferred to analyse the effect of these imperfections. Additionally, a comparative study between the effects of two different types of imperfection statistics – section-independent 'generalised' statistics and section-specific 'particular' statistics – is performed. This is to assess the legitimacy of using the generalised statistics of imperfection, in the case that a particular statistic is unavailable. As an initiatory work in this area from a statistical perspective, our study is limited to a single lipped channel section with a *Type 1* deformation (Fig. 1). In this work, the yielding of the material is included in the member behaviour, however, torsional and flexural-torsional effects are avoided using suitable constraints.

4. Critical load analysis of the channel section

A finite element (FE) approach is adopted for the buckling analysis of the member with some geometric imperfection, in order to properly capture the failure behaviour, including the interaction with local and distortional buckling modes. Second-order inelastic analyses (that is, including both material and geometric nonlinearity) are used to arrive at the 'critical load' for the member [17]. Since this load is obtained from the load-deformation curve of the member, the analysis lets us observe the sequence of local/distortional buckling and the overall member buckling.

The lipped channel section selected for this study is 362S162-68 with the following dimensions: depth of the web = 92 mm (3.625 in), width of the flange = 41.3 mm (1.625 in), and thickness = 1.7 mm (0.068 in). Six different lengths of the section are considered in order to study the behaviour for different nondimensional slenderness ratios (λ_c) in the range of 0.5–2.5, where λ_c is defined as [3]

$$\lambda_c = \sqrt{\frac{F_y}{F_e}} \tag{1}$$

where F_y is the material yield stress, and F_e is the minimum critical elastic column buckling stress (considering only the flexural mode).