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Initial stiffness evaluation of reverse channel connections in tension and compression

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ABSTRACT

The so-called Reverse Channel connection has been conceived for the purpose of accommodating the thermal expansion of beams so that premature failure due to thermal buckling is avoided. The connection is made of a channel-shaped element, welded along the tips of its flanges onto the face of a hollow section column; an endplate welded on the beam is bolted onto the web of the channel. In a fire situation, the thermal expansion of a reverse-channel supported beam causes extensive bending deformation of the connection, therefore preventing the development of significant axial stress in the beam. Furthermore, this connection offers a high rotational capacity, if designed properly, which is beneficial in a fire situation where excessive deflections of beams can be expected.

This paper aims to provide analytical stiffness assessment tools for reverse channel connections in compression and tension under uniform temperatures. The proposed analytical models are compared to results of Finite Element simulations, which in turn have been benchmarked with experiments. In addition, a comprehensive parametric study is conducted in order to identify all influencing factors on the initial stiffness response: reverse channel geometry and thickness, plate thickness, bolt position, and bolt diameter. Correction factors that account for 3D effects and bolt size are presented and discussed.

The obtained expressions for the reverse channel stiffness are found to provide an accuracy that is acceptable for structural applications and can, therefore, be used as a design tool.

1. Introduction

European design codes [1,2] provide relatively scarce information concerning the behaviour of steel connections at elevated temperatures. However, observations made in real fire situations, [3,4] as well as during the Cardington full-scale fire tests [5] have clearly shown the importance of joint behaviour with respect to the robustness. During a fire the structure undergoes essential changes of its behaviour, mainly due to temperature-induced material properties degradation and the development of internal forces owing to restrained thermal deformations. Ideally, connections will have to perform well with respect to three aspects: (a) provide a deformation capacity high enough to accommodate the thermal elongation of a beam without significant axial forces during the first stage of the fire, (b) accommodate the excessive end-rotations of the beam that develop during the runaway stage and (c) undertake the tensile forces that arise during the cooling phase. In this respect the initial behaviour of the connection is characterised by high compliance thus making it a semi-rigid connection in the sense of the axial expansion of the beam. The present paper deals with an increasingly popular solution that does have the capacity to provide the above characteristics: the reverse channel (RC) connection (see Fig. 1). This connection is particularly suited for beam to column joints, working equally well for either circular or rectangular (concrete-filled) hollow-section columns; it is made up of partial-depth endplates (EP), web cleats or conventional endplates bolted onto the web of the reverse channel section, while the flanges of the channel section are welded to the column face [6].

As mentioned above, this type of connection being relatively new, very few results, especially analytical solutions suitable for design, exist so far. Based on the experiments performed by Lopes et al. [7] and Jafarian and Wang [8,9], two plastic hinge models for reverse channels subjected to tension and compression have been developed in [9]. However, although these models seem to be capable of predicting the resistance and displacement at failure with satisfactory accuracy, to the authors' understanding, a weakness as far as initial stiffness is concerned seems rather obvious.

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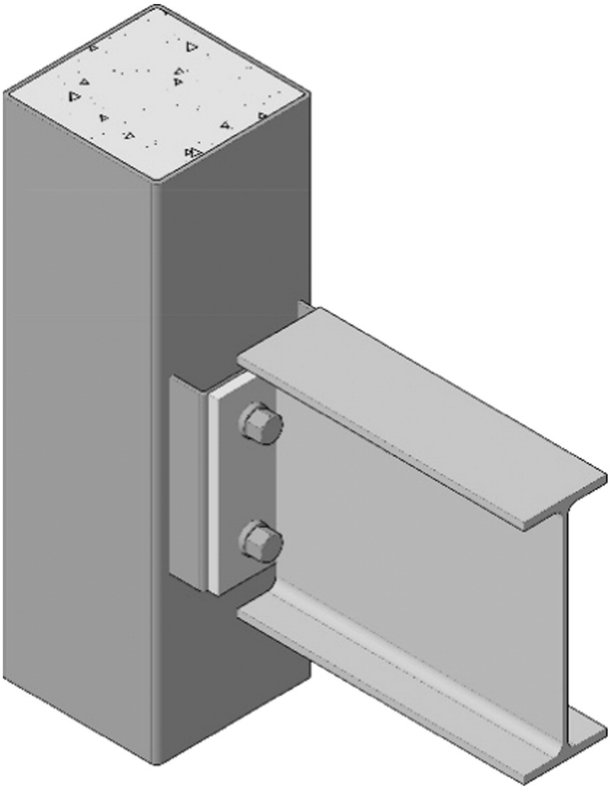

Fig. 1. Reverse channel joint–partial-depth endplate configuration.

Furthermore, Lopes et al. [7] showed that the existing analytical models for resistance and stiffness available in the literature for RHS columns [10] do not apply to the reverse channel section. Moreover, another analytical model for the initial stiffness proposed by Liu, Málaga-Chuquitaype and Elghazouli [11,12] for combined channel/angle connections to tubular columns (open beam-to-tubular column) does not fit the case of the reverse channel–endplate connections considered here, because of obvious differences in geometry.

It can therefore be safely stated that the research related to the evaluation of the initial stiffness is still at a very early stage. In the context of the component method [1], a characterization of the behaviour of the new component – the reverse channel section – in tension and in compression is necessary.

In this respect the present paper provides analytical solutions that capture the initial stiffness of reverse channel–partial-depth endplate connections, in both compression and tension under uniform temperatures. A series of experiments was performed at the University of Coimbra to evaluate the behaviour of channel sections loaded transversely through their web at ambient and elevated temperatures [7]. The experimental programme consisted of 13 tensile and 8 compressive tests aiming to evaluate the overall behaviour of the component that is, establishing relations between force, displacement and temperature, as well as assessing the influence of the geometry of the connection. For the purpose of verifying these experimental results, 3D Finite Element simulations of the tests have been carried out with the commercial software ABAQUS [13]. The hence calibrated Finite Element models are used in the present work for the purpose of assessing the accuracy of the analytical stiffness estimates for the reverse channel sections. In addition, analytical expressions are developed and validated against a wide range of 2D and 3D simulations.

2. Validation methodology of the initial stiffness estimates

The essence of the present work is the derivation and verification of analytical expressions that capture the initial stiffness of the reverse channel connection; these are derived in Section 4. As these expressions are based on a two dimensional beam theory approach, their validity is tested against plane stress FE results where the only source of non-linearity is the unilateral contact between the reverse channel and the beam endplate. In fact, the mechanism of unilateral contact is found to be the major factor affecting the accuracy of the analytical expressions. Performing the initial validation of the analytical expressions against plane stress FE results is chosen for two reasons: first, a beam theory result may only be compared against plane stress as bending theory in fact is an approximation to plane stress. The second reason is the lower computational cost of plane stress models that allows the easy generation of a far greater number of numerical results. In this way, it is possible to test the analytical expressions under a large range of combinations of geometric parameters.

The next step is to validate the analytical expressions against 3D FE results. This entails two steps:

(a) Studying the deviation between the plane stress and the three dimensional FE models with respect to the length of the reverse channel. This leads to the estimation of a 3D-effect correction.
(b) Studying the deviation between the analytical result and the 2D FE model for a reverse channel length value requiring no 3D-effect correction. This comparison will reveal discrepancies owing to the severe geometry simplification as beam theory was used for the derivation of the analytical expressions.

Step (a), which constitutes a validation of the plane stress approach, is covered in Section 5.3. Comparisons related to step (b) are discussed in Sections 5.1 and 5.2 where the performance of the analytical approach is evaluated. Last, the issue of the effect of the bolt size is addressed in Section 5.4.

3. Numerical work

3.1. The experimentally calibrated non-linear 3D FE analyses

The first part of the numerical work done in the context of this paper concerns the calibration of a Finite Element model against experimental data from [7]. The details of the comparison with the experiments have been presented in [13] and will not be repeated here. It suffices to say that it is a highly realistic model where various details (bolt head volume, washers and weld fillets) are faithfully reproduced. Being capable of accurately reproducing the behaviour observed in the experiments, this 3D FE model is used as a template against which the analytical estimates of the initial stiffness are compared.

Making use of the aforementioned 3D Finite Element models, a parametric study (Table 1) is carried out including both ambient and elevated temperatures. Two different types of reverse channel sections, rolled parallel flange channel (PFC) and tube cut-outs are used.

This study investigates the effects on initial stiffness of the following parameters (see Fig. 2): i) leg length, H; ii) bolt spacing, a; iii) endplate thickness, t_{EP}; iv) reverse channel thickness, t_f and t_w; v) rolled channel (PFC) or constant thickness channel cut from a tube, and vi) temperature.

Table 1 presents an overview of the parametric study, showing the parameters' range of variation. Of all the possible combinations, 100 3D non-linear Finite Element models are solved for both tension and compression. Material and geometric non-linearities are considered (including large strains). The load, applied as imposed displacement of the beam web, is increased until convergence failure of the FE code occurs. In this way, both the initial stiffness as well as the nonlinear behaviour of the connections can be evaluated.

3.2. The FE study used to evaluate the 3D correction for plane stress

A slight variation of the FE model used in Section 3.1 is implemented in the context of linear elastic FE analysis with unilateral contact to