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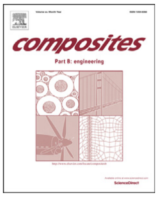

FEM simulations and rotation capacity evaluation for RHS temper T4 aluminium alloy beams

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ABSTRACT

The aim of this work is the development of an empirical relationship for evaluating the rotation capacity of RHS temper T4 aluminium alloy beams subjected to non-uniform bending. The proposed relationships are based on the numerical results coming from an extensive parametric analysis performed by means of FE code ABAQUS, which gains insight into the influence of all the geometrical and mechanical parameters affecting the ultimate behaviour of aluminium alloy beams. In particular, the influence of the flange slenderness, the influence of the web restraining effect related to the flange-to-web slenderness ratio and the influence of the moment gradient are investigated. The modelling of the material is carried out by adopting the constitutive law proposed by Eurocode 9, based on the Ramberg-Osgood model whose shape factor characterises the hardening behaviour of the material. The investigations concern these factors considered separately as well as their interaction. The results are herein reported with reference to temper T4, i.e. an alloy characterised by a significant hardening behaviour, and show the importance of some of the investigated parameters on the maximum flexural resistance, corresponding to the complete development of local buckling of compressed flange, and on the rotation capacity of aluminium alloy beams. Successively, by means of monovariate and multivariate non linear regression analyses, empirical relationships are provided in order to predict both the ultimate bending resistance and the rotation capacity of RHS temper T4 aluminium alloy beams starting from their geometrical and mechanical properties.

1. Introduction

The evaluation of the rotation capacity of metal members has been the subject of several studies over the years, because it is needed to allow the redistribution of internal stresses in structures, in particular when plastic strain concentrations occur, as well as to assure the complete development of the plastic reserves of redundant structures allowing the development of a kinematic collapse mechanism before local failure and, finally, to guarantee the energy dissipation capability desired in case of severe seismic actions. Therefore, the rotation ductility is one of the parameters usually employed to synthesize the ultimate behaviour of structural members. It is conventionally defined as a function of the inelastic rotation that the member is able to sustain given a certain level of bending moment, usually fixed as the full plastic bending moment, which the member has to continue to withstand despite of plastic deformations. For these reasons, modern codes, such as Eurocode 3 (EC3) [1], divide cross sections into different behavioural classes; in particular, four classes are considered. First-class sections are able to develop their whole plastic resistance with high plastic deformation capacity. The whole plastic resistance can be also attained in the case of second class sections, but with a limited plastic deformation capacity. Third-class sections locally buckle before the complete development of their plastic reserves, so that their plastic deformation capacity is very limited. Finally, fourth-class sections locally buckle in the elastic range without exhibiting any significant plastic rotation capacity.

In the case of aluminium structures, Eurocode 9 (EC9) [2] provides a classification system based on experimental tests that accounts for the slenderness of the plate elements composing the cross-section. In particular, the width-to-thickness ratio b/t and the conventional elastic stress limit $f_{0.2}$ are recognized as the only parameters governing the occurrence of local buckling either in elastic range or in plastic range and are used for the classification of

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sections.

In order to enhance the knowledge of the inelastic behaviour of aluminium members, a significant number of experimental tests is needed. Unfortunately, the current state of experimentally based knowledge is characterised by few experimental tests concerning extruded aluminium profiles subjected to moment gradient loading which have been carried out at Norwegian University of Science and Technology [3]. Conversely, a wide experimental campaign devoted to the evaluation of the buckling strength of heat-treated aluminium alloy sections has been developed at University of Salerno [4], but limited to uniform compression. Even though this latter campaign of experimental tests does not consider the effects of moment gradient along the member, it has led to the classification rules reported in Eurocode 9 [2], [4]. In addition, regarding members subjected to bending, experimental results available for aluminium alloy beams are quite low [3] if compared with the large number of experimental studies reported in the technical literature dealing with the rotation capacity of steel and composite members [5–9]. However, wider and even more exhaustive investigations for the prediction of the rotation capacity of members can be performed through FEM models, especially, by means of ABAQUS computer program [10–11]. In fact, many researchers have simulated the behaviour of extruded aluminium thin-walled RHS beams subjected to uniform moment loading [12] and to gradient moment loading [13–15], or the behaviour of tubular continuous aluminium alloy beams [16], [17]. In particular, by only changing the material characteristics, De Matteis et al. [18]. performed a numerical study to assess the rotation capacity of aluminium alloy members developing a wide parametric analysis taking into account the flange slenderness ratio, the web restraining action, the section shape factor of the material stress-strain curve as well as the moment gradient along the member.

With reference to EN-AW 6061 and EN-AW 6082 aluminium alloys, temper T4 [2], this work aims to further advance such study [18] by developing a wider parametric analysis taking into account initial geometrical imperfections, the influence of the moment gradient along the member and different values of both the flange slenderness ratio and of the parameter related to the web restraining action, through FEM models. In particular, the analyses are carried out considering different geometrical characteristics and the constitutive law provided by Ref. [2]. Temper T4 is a material naturally aged at room temperature and is more ductile if compared with temper T6, because it exhibits a significant strain hardening. In fact, temper T4 shows a quite low yield point resistance that makes it suitable to be used for dissipative devices as well as low yield-point steel [19]. The results herein presented can be useful for the development and validation of semi-empirical [20] or analytical [21–22] approaches to estimate the rotation capacity of members. In particular, in the final part of the present paper, empirical relationships for evaluating both the ultimate bending resistance and the rotation capacity of RHS aluminium alloy beams are provided. By means of both monovariate and multivariate non linear regression analyses, relationships for predicting, starting from their geometrical and mechanical properties, both the ultimate bending resistance and the rotation capacity of RHS temper T4 aluminium alloy beams have been derived and proposed showing their accuracy by comparing the predicted values with the results coming from FE simulations.

2. Finite element model

2.1. Analysed scheme and model geometry

The aluminium beams considered in this study are extruded profiles with Rectangular Hollow Section (RHS) made of Temper T4 material. Aiming to evaluate the ultimate behaviour in terms of moment-rotation of these RHS aluminium alloy beams subjected to non-uniform bending, they are assumed to be simply supported and vertically loaded at mid-span. This three point bending scheme is usually adopted both in experimental and in numerical tests [3], [18]. However, thanks to the symmetry of the structural scheme, the finite element model can be simplified by using a simple cantilever scheme whose length is equal to the half of the specimen length. The cantilever length has been extended approximatively for 50 mm beyond the load point (Fig. 1). A suitable numerical model has been set up by using the ABAQUS computer program [10]- [11] for non linear finite element analyses. The geometry of the model adopted in the study is depicted in Fig. 1. Four-node general shell elements with reduced integration (S4R) have been used by adopting a mesh refinement that varies longitudinally as shown in Fig. 1. The numerical analyses have been carried out in displacement control by using the “Static, General” procedure which automatically increments the step size. The analysis accounts both for geometrical and mechanical non linearities.

The displacement has been applied at the section of the cantilever depicted in Fig. 1 where a coupling constrain has also been introduced to rigidly connect all the section points in order to simulate a rigid diaphragm. Finally, with the scope to take into account the influence of initial imperfections, their shape has been assumed as corresponding to the most likely instability mode. To this aim, the compressed flange buckling mode has been derived by a linear perturbation buckling analysis carried out on the same structural model already described. The obtained main eigenmode (Fig. 2), properly scaled to the desired magnitude, has been applied to the original model in order to take in account the imperfection effects on the overall behaviour of the member. The magnitude of the imperfections, i.e. the scale factor of the main eigenmode, has been assumed so that the maximum out-of-plane initial deformation of the flange plate is equal to b/500 [13].

2.2. Material model

The beams investigated in the current study are extruded profiles of EN-AW 6061 and EN-AW 6082 aluminium alloys of temper T4, i.e. naturally aged at room temperature. According to Eurocode 9 [2], Ramberg-Osgood (R-O) model may be applied to describe the stress-strain relationship in the form $\varepsilon = \varepsilon(\sigma)$:

$$\varepsilon = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{f_{0.2}}\right)^{n} \tag{1}$$

In particular, Eurocode 9 [2] provides for temper T4 a value of $f_{0.2}$ (stress corresponding to 0.2% plastic strain) equal to 110 MPa while the value of the exponent n is equal to 8.

However, according to a previous study [3], the Hopperstad exponential stress-strain model [23] is more suitable for the implementation in ABAQUS computer program [10]- [11]. Therefore, in this study, the Hopperstad model has been properly calibrated to fit the Ramberg-Osgood stress-strain curve provided by Eurocode 9. The uniaxial true-stress true-strain model adopted for the finite element simulations is provided by the following equation:

$$\sigma = Y_0 + Q\left[1 - exp\left(-C\varepsilon_p\right)\right] \tag{2}$$

where σ is the current stress, ε_p is the plastic strain and Y_0 is the conventional elastic limit strength equal to $f_{0.2}$. In the model herein described, Q and C are two material constants, determining the magnitude of the strain hardening and the shape of the curve, respectively. In order to best fit the Ramberg-Osgood model

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