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Computational modelling of flange crushing in cold-formed steel sections

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ABSTRACT

The computational modelling of the flange crushing phenomenon in cold-formed steel profiles is described in this paper, with particular emphasis to the development of shell finite element (SFE) models and performance of quasi-static analyses with an explicit integration scheme. Web crippling failure is widely recognised as the most relevant collapse mode of cold-formed steel members subjected to transverse concentrated loads. However, it has been experimentally and numerically observed that a somewhat different collapse mode may occur, due to the heavy stress concentrations stemming from the adoption of narrow bearing plates. This phenomenon, termed flange crushing, should not be confused with web crippling. Usually, the web crippling phenomenon is numerically investigated by means of non-linear static SFE models with an implicit integration scheme. In this study, SFE models are developed in ABAQUS code to study the flange crushing failure of a plain channel beam subjected to Internal Two Flange (ITF) loading conditions. These models are described in detail, as well as additional modelling concerns regarding quasi-static analyses and the explicit integration method. Different parameters are discussed in this article and the numerical results obtained are commented throughout. Such parameters include the (i) SFE type and mesh, (ii) load rate, mass scaling, adoption of smoothed displacement amplitude curves and control of inertial effects, (iii) contact and friction definitions, (iv) effects of forming cold-work and manufacturing process and (v) geometrical imperfections. Finally, the load–displacement response obtained with the quasi-static model and an equivalent non-linear static analysis are compared with the experimental test curves. It is concluded that very good results are achieved with the quasi-static approach, not only in terms of the ultimate load prediction, but also regarding the post-collapse load–deflection curve and the failure mechanism.

1. Introduction

Cold-formed steel members are structural elements obtained through the mechanical folding of thin steel sheets. Due to their reduced thickness, these members are very sensitive to various buckling phenomena. Besides failures stemming from local and distortional buckling, the web crippling failure arising from the action of transverse concentrated loads (and/or support reactions) often governs the design of cold-formed steel beams. The compressive normal stresses acting in the transverse direction, as well as the shear stresses, are mutually responsible for substantial strength degradation, due to gradual yielding and spread of plasticity.

Web crippling failure is characterised by the simultaneous occurrence of localised buckling (instability) and a yield line mechanism (plasticity) in the web panel. In the past few years, several investigations have been devoted to the subject of web crippling failure of cold-formed steel beams. While some of them are related with experimental testing [1–6], others focus on numerical studies, particularly those based on shell finite element (SFE) analyses [6–12].

Nevertheless, several cases have been identified where web crippling is not prevalent, due to the reduced width of the load bearing and support plates, particularly in Interior Two Flange (ITF) load configurations. Similar observations were reported by Heiyanthuduwa [5], for other web crippling loading conditions. It was concluded that different load–displacement responses may be obtained, which are mainly influenced by the (i) load bearing/support width and the (ii) corner bend radius. The above author describes a collapse mode involving high stress concentrations in the top corner region, which was observed in structural members

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Fig. 1. Flange crushing in a hat-section beam acted by a concentrated load.

with large corner radii and loaded through narrow bearing plates. As far as load–displacement curves are concerned, Heiyanthuduwa [5] describes that this behaviour is characterised by a more gradual transition between the linear and post-collapse branches.

Fig. 1 illustrates the collapse of a cold-formed steel hat-section subjected to a concentrated load, which can be viewed as flange crushing. This phenomenon is highly complex, particularly due to (i) the non-uniform stress distributions generated by the applied loads, (ii) the steel non-linearity (including strain-hardening), (iii) the eccentricity between the load application and the web plane, imposed by the rounded corners, and (iv) the rotational restraint imposed by the flange on the web, usually due to fastened connections (see Fig. 1).

Regarding the numerical investigation of the web crippling phenomenon, the majority of the recent investigations have relied on non-linear static analyses employing SFE models with complex contact definitions [9,10,13]. However, significant drawbacks have been found in this type of analyses. Kaitila [12,14] developed SFE models to investigate the web crippling behaviour of cold-formed steel cassette sections and initially adopted non-linear static analyses performed in ABAQUS/Standard [15], which were found to lead to significant convergence problems. As a consequence, this author switched to a quasi-static dynamic approach to the analysis, using the ABAQUS/Explicit [15] algorithm. According to the ABAQUS User's Manual [15], this numerical package is particularly successful in simulating high-speed dynamic events, as well as quasi-static problems. Even if the above study contains some information regarding the ABAQUS modelling definitions and contact formulations, the majority of the available publications lack some detail regarding the SFE model.

The main objective of this article is to present a thorough analysis of the different parameters involved in the simulation of a specimen subjected to web crippling/flange crushing collapse, considering a somewhat unusual approach, i.e. the quasi-static analysis with an explicit integration scheme. Even if part of this information is better contextualised when using ABAQUS, the majority of the parameters discussed here may also be relevant when using other software packages. Moreover, it is likely that a significant portion of this information may also be relevant for the numerical (SFE) simulation of other structural problems involving thin-walled structural systems.

2. Static vs. quasi-static models

As mentioned earlier, non-linear static analyses currently prevail in the computational modelling of cold-formed steel profiles. The generic formulation of a non-linear static equilibrium equation reads

$$K(u)u = f \tag{1}$$

where (i) u stands for a generalised displacement vector, (ii) f denotes the vector of applied loads, and (iii) $K(u)$ is the stiffness matrix, which depends on the displacement vector components u_i, thus corresponding to a non-linear system of algebraic equations, comprising both physical and geometrical non-linear effects.

The ABAQUS/Standard solver adopts the modified Riks method to carry out the non-linear static analysis, together with an implicit integration scheme – an incremental-iterative scheme is absolutely necessary to solve the non-linear system. The displacement vector increment between two different equilibrium configurations may be expressed by

$$u_{k+1} - u_k = -T^{-1}(u_k)(K(u_k)u_k - f)d_k \tag{2}$$

where, as usual, T stands for the tangent stiffness matrix, given by

$$T(u_k) = K(u_k) + \frac{K(u_k)}{du} u_k \tag{3}$$

As pointed out previously, non-linear static analyses may evidence significant convergence difficulties [12], particularly in problems involving large numbers of degrees of freedom and complex contact specifications. The processor determines the system eigenvalues, whose sign (positive, negative) governs the stiffness matrix definiteness. Negative eigenvalues are associated with numerical instabilities and divergence, which may interrupt the numerical calculations. Even if the processor overcomes these numerical instabilities, the numerical solver may fail to reach a new equilibrium configuration, in which case it will unload along the previously determined equilibrium ascending path.

Additionally, an experimental set-up involves the motions of the bearing plates against the test specimen, with a prescribed load rate. Given the extremely small load rate values, these problems are not truly dynamic – at least, not in the sense often attributed to the word "dynamic" (e.g., in metal forming, impact analysis and energy absorption). A rational alternative is to consider a quasi-static approach, for which the ABAQUS User's Manual [15] suggests the adoption of an explicit integration scheme.

A quasi-static analysis is based on the solution of the dynamic equilibrium equation,

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t) \tag{4}$$

where M is the mass matrix, C is the damping matrix, K is the linear stiffness matrix, $\ddot{u}(t)$ is the acceleration vector, $\dot{u}(t)$ is the velocity vector and $u(t)$ is the displacement vector. The displacement, its derivatives and the force vector are now time-dependent functions and the dynamic equilibrium equation requires additional terms, namely (i) inertia forces due to acceleration ($M\ddot{u}(t)$) and (ii) damping forces ($C\dot{u}(t)$) associated with potential frictional contact. In the context of quasi-static analyses, both these terms should have a minor impact, when compared with that of the stiffness term.

Experimental set-ups often adopt displacement control to apply load at a constant load rate, in which case the acceleration term in Eq. (4) should be null, with the exception of the very early instants of the test, when the load cell begins moving. Additionally, the load cell motion speed is often minute (e.g. 1.0 mm/min [4]), which leads to the development of marginal damping forces.

Two alternative integration schemes are available in ABAQUS [15], namely implicit integration in ABAQUS/Standard and explicit integration in ABAQUS/Explicit. Sun et al. [16] compared these two integration schemes in the context of the solution of dynamic problems. One fast and one slow event were tested and it was concluded that the implicit integration scheme is advantageous for the slow contact problem, since the explicit method often leads to