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Residual stresses and initial imperfections in non-linear analysis

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ABSTRACT

When non-linear finite element analysis (FEA) of cold-formed thin-walled steel sections subject to compression is carried out, an initial perturbation must be introduced in the model in order to trigger the failure due to instability. The most usual way is to introduce an equivalent initial imperfection in the model (conventional models) that includes the effects of geometric imperfections and residual stresses due to the roll-forming manufacturing process, possible loading eccentricity, etc. It is thought that results would be more accurate if the actual measured geometric imperfections and the actual residual stresses induced from manufacturing were introduced. This paper presents the determination of residual strains and stresses generated in the cold roll-forming process of a typical rack section (without perforations) from steel sheet, using FE simulation. The obtained residual elastic and plastic strains have then been incorporated in the model, and used as an initial strain state in the non-linear finite element analysis. The results obtained agree well with the experimental results for short and intermediate length columns, where the failure mode is predominately local and distortional.

1. Introduction

For numerical prediction of the ultimate strength of cold-formed thin-walled steel sections under compression, a finite element model including geometric and material nonlinearities is commonly used.

The standard approach consists of modelling imperfection distribution as buckling modes (linear buckling analysis). Generally, the first buckling mode is selected for use in subsequent nonlinear analysis. As for imperfection magnitudes, values from standards and literature are usually taken. These values include the effects of residual stresses from the cold roll-forming process and other factors such as loading eccentricity. Therefore, both distribution and magnitude are more a modelling convenience than a physical reality.

In this section, a summary of recent research on geometric imperfections and residual stresses in finite element models is presented. Refs. [2–9,14–16,19,25] commented below have already been discussed in [1], which contains a comprehensive analysis of computational modelling of cold-formed steel.

First, it is worth recalling that both ultimate strength and post-buckling mechanisms are imperfection sensitive [2–4]. Consequently, geometric imperfections have a role to play in the details of the buckling mode initiated in the load response [4]. These imperfections can be included in the model as a modelling convenience. In this case, their distribution is typically the first buckling mode, although sometimes higher modes have to be used to obtain accurate results. The column's initial imperfections can also be included as different linear combinations of the critical buckling mode shapes obtained through preliminary linear stability analysis [5]. With regard to the magnitude of the imperfection, it may be "fit" so that predicted strength matches a test [6,7], or it may be "fit" so that instabilities under study are appropriately triggered [5]. However, generally the magnitude is either taken as a function of plate thickness (i.e. $0.1t$) or slenderness [5,8–10].

On the other hand, many researchers have used measured geometric imperfections to study their effect on the ultimate strength of cold-formed steel members [9,11–13]. Statistical information on local and distortional buckling imperfection magnitudes that were measured on actual cross-sections is provided in [9]. This paper shows values with 25%, 50% and 75% of probability of exceedance for both types of imperfections. Schafer's research group is continuing this work in imperfection spectra [1]. Statistical information on global imperfections from 210 cold-formed steel members is also provided in [14–16], where global bow, camber, and twist were measured at seven different manufacturing plants. More recent work in this area from the same group has been published in [17]. Initial geometric imperfection and residual stress measurements in a hollow flange channel beam are reported in [18].

A mechanistic model for prediction of residual stresses and strains is provided in [19], which allows the modeller to consider

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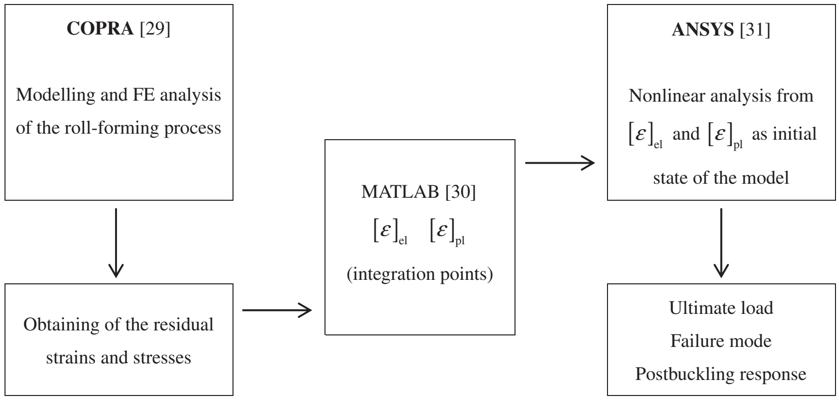

Fig. 1. Outline of the process followed.

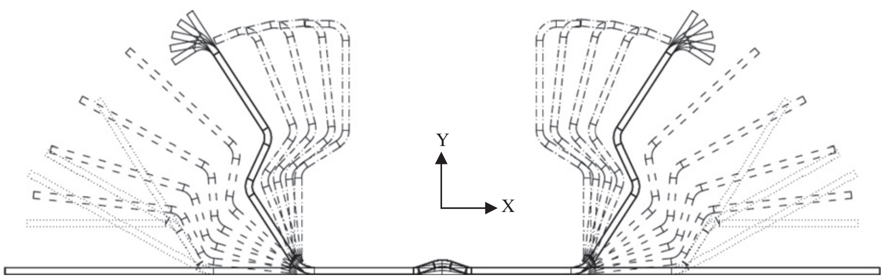

Fig. 2. Flower pattern with 20 forming stands.

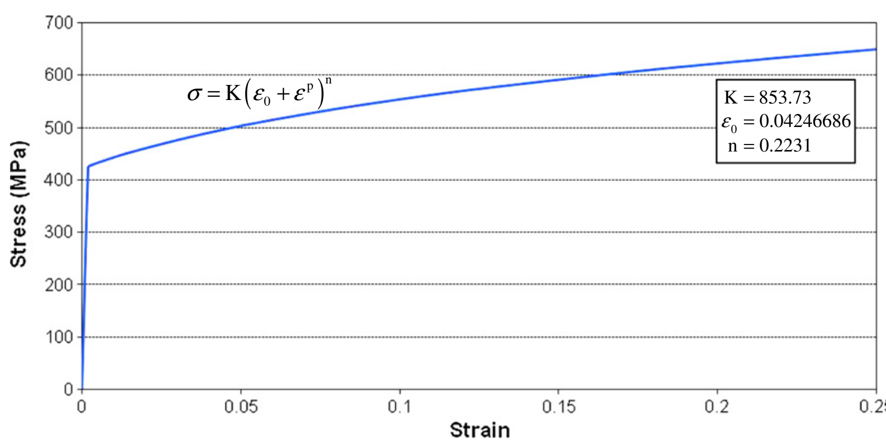

Fig. 3. Swift's curve used to define with large plastic deformation.

their effects by generating a more accurate set of initial conditions. The analytical and numerical predictions of residual stresses in press-braked carbon steel and stainless sections are reported in [20–23]. The nonlinear buckling analysis of C-sections under compression is described in details in [24] in which the methods presented in [20–23] are incorporated to define initial residual stresses.

In this paper, a more sophisticated approach is used to model the behaviour of cold-formed members. The methodology shown in references [25–28], where finite element analyses of cold roll-formed steel sections are carried out through modelling the actual manufacturing process, is applied. The aim of the present investigation is to simulate the manufacturing process of a thin-walled open section in order to obtain the residual stress and strain distribution over the cross-section, and introduce them into the finite element model as an initial state for the subsequent nonlinear analyses.

Attention is focused on the stability under compression of uprights for pallet racking systems and their buckling modes of failure.

The procedure followed is described in Fig. 1. Section 2 presents the numerical modelling and FE analysis of the manufacturing process of the profile from a steel sheet. Section 3 explains how the residual strain tensors at the integration points have been stored and incorporated as an initial state of the model for performing the nonlinear analysis. Section 4 compares the numerical and experimental results for different column lengths.

2. Simulation of the roll forming process

COPRA FEA RF (a non-linear finite element analysis module) [29] has been used to simulate the roll forming operation. This module imports data directly from COPRA RF (a deformation technology module), which acts as a pre-processor for the finite element simulation.

First it is necessary to design the flower pattern, that is, the diagram of the different stages of the roll-forming process of the profile. After designing the forming line stations, the finite element