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Residual stresses in press-braked stainless steel sections, II: Press-braking operations

W.M. Quach [a], J.G. Teng [b,*], K.F. Chung [b]

[a] Department of Civil and Environmental Engineering, University of Macau, Macau, China

[b] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

The manufacturing process of cold-formed thin-walled steel members induces cold work which can be characterized by the co-existent residual stresses and equivalent plastic strains and has a significant effect on their structural behaviour and strength. The present paper and the companion paper are concerned with the prediction of residual stresses and co-existent equivalent plastic strains in stainless steel sections formed by the press-braking method. This manufacturing process consists of the following two distinct stages: (i) coiling and uncoiling of the sheets, and (ii) press-braking operations. This paper first presents an analytical solution for the residual stresses and the co-existent equivalent plastic strains that arise from the second stage while a corresponding analytical solution for the first stage is presented in the companion paper. In both solutions, plane strain pure bending is assumed and the effect of material anisotropy is taken into account. On the basis of these two analytical solutions, an analytical model is presented to predict residual stresses and equivalent plastic strains in press-braked stainless sections. The predictions of the analytical model are shown to be in close agreement with results from a finite element-based method, demonstrating the validity and accuracy of the analytical model. The analytical model provides a much simpler method for the accurate prediction of residual stresses and equivalent plastic strains in different parts of a press-braked stainless steel section than a finite element-based method.

1. Introduction

The manufacturing process of a cold-formed thin-walled steel section induces significant cold work in the section and has a significant effect on their structural behaviour and strength. This cold work can be characterised by the co-existent residual stresses and equivalent plastic strains in the section, with the latter representing the strain hardening of the steel induced by cold work. This paper and the companion paper [1] are concerned with the development of an accurate analytical model for the prediction of residual stresses and equivalent plastic strains in press-braked stainless steel sections. The manufacturing process of press-braked sections consists of two distinct stages: (i) coiling and uncoiling of sheets, and (ii) press-braking operations. In the companion paper, an analytical solution has been presented for the residual stresses and equivalent plastic strains that arise from the first stage. In the present paper, an analytical solution is presented for the residual stresses and equivalent plastic strains that arise from the second stage. On the basis of these two analytical solutions, an analytical model is then presented to predict residual stresses and equivalent plastic strains in press-braked stainless steel sections.

In the companion paper, difficulties and limitations with laboratory measurements of residual stresses and strain hardening in cold-formed steel sections have been discussed. Nevertheless, observations from existing experimental studies [2–7] on residual stresses in cold-formed carbon steel and stainless steel sections have led to the following useful conclusions: (1) residual stresses in roll-formed sections are larger than those in press-braked sections; (2) the inner surface of a cold-formed section is generally subject to compressive residual stresses while the outer surface is generally subject to tensile residual stresses; and (3) the magnitudes of residual stresses in the corner regions (curved parts) of a cold-formed open section are generally higher than those in the flat portions (e.g. webs, flanges and lips).

In order to overcome the difficulties encountered in experimental measurements of residual stresses and strain hardening in cold-formed sections, the alternative of developing theoretical models has been pursued for cold-formed carbon steel sections by a number of researchers [8–12] as reviewed in the companion paper. Among these theoretical studies, only Quach et al. [11,12] have properly accounted for the effect of the coiling and uncoiling of sheets. However, due to the material anisotropy and the nonlinear

* Corresponding author. Tel.: +852 2766 6012; fax: +852 2334 6389.
E-mail address: cejgteng@polyu.edu.hk (J.G. Teng).

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stress–strain behaviour of stainless steels, the method proposed by Quach et al. [11,12] for cold-formed carbon steel sections cannot be directly adopted for the prediction of residual stresses and equivalent plastic strains in cold-formed stainless steel sections.

This paper presents an analytical model for predicting residual stresses and equivalent plastic strains in press-braked stainless steel sections. Instead of the semi-analytical approach of Quach et al. [11,12], the present method is completely analytical and comprises two analytical solutions to describe the two distinct stages of the manufacturing process. In both solutions, plane strain pure bending is assumed and the effect of material anisotropy is taken into account. The validity and accuracy of the model is demonstrated by comparing its predictions with those from finite element simulations. A similar but less involved model has also been developed for carbon steel sections [13].

2. Scope of work

It is important to recognise that the residual stresses in the flat portions of a press-braked section are only due to the coiling–uncoiling process while the residual stresses in the corner regions are mainly due to the cold bending of press-braking operations. This observation means that for a press-braked stainless steel section, the residual stresses and equivalent plastic strains in the flat portions can be determined using the analytical solution presented in the companion paper while those in the corner regions can be determined using the separate analytical solution for the cold bending of press-braking operations presented in Section 3 of the present paper. To establish this solution, the analytical formulation for small-curvature pure bending involved in the coiling–uncoiling process presented in the companion paper is extended to deal with large-curvature bending involved in press-braking operations to produce corners of a press-braked section. In Section 4, the effect of some simplifying assumptions employed in developing the analytical solution for large-curvature bending is examined by comparing analytical predictions with finite element results. On the basis of the two analytical solutions for the two separate stages of the manufacturing process, an analytical model for predicting residual stresses and equivalent plastic strains in stainless steel sections is presented in Section 5. The accuracy of the model is also demonstrated in Section 5 by comparing its predictions with those from the finite element-based method which has already been presented in Refs. [11,12]. Both the analytical model and the finite element-based method are further explained in Fig. 1.

3. Analytical solution for cold bending

3.1. Assumptions and general issues

Results of the finite element-based method presented in Ref. [12] show that press-braking operations induce cold work locally at the corner regions of a press-braked section and basically do not affect the stress state in the flat portions. This means that the residual stresses in the flat portions are mainly derived from the coiling and uncoiling of the steel sheet and can be determined by means of the analytical solution for the coiling–uncoiling process. Furthermore, as shown in Ref. [12], the residual stresses within a corner of a cold-formed section vary across the thickness but are fairly uniform around the perimeter of the bent corner. Since the bending curvature of a corner is usually much larger than the coiling curvature, the residual stresses in the corner regions of a cold-formed section are not significantly affected by the coiling–uncoiling process. Hence, the cold bending of an uncoiled sheet into the corners of a cold-formed section can also be modelled as a problem of plane strain pure bending of a sheet into a large curvature in the transverse direction with the preceding deformation history of the coiling–uncoiling process ignored. The analytical solution for the coiling of stainless steel sheets presented in the companion paper [1] is extended in this section to model residual stresses due to the cold bending of a stainless steel sheet into the corners of a press-braked section. Most of the equations presented in the companion paper can still be used but some modifications are needed to develop the analytical solution for large-curvature cold bending.

For consistency, it is necessary to use the same coordinate system and the same uniaxial stress–strain curve to describe non-linear strain-hardening for both stages of the manufacturing process. Therefore, in the modelling of the cold bending of press-braking operations, the initial yield stress σ_{0L} in the longitudinal direction is also used as the reference yield stress and the uniaxial stress–strain curve of the longitudinal direction (Eq. (1) in the companion paper) is again adopted to describe the non-linear strain-hardening behaviour. It should be noted that although the reference yield stress in the same direction is used for both stages, the direction of sheet cold bending into corners (the transverse direction) is orthogonal to the direction of sheet coiling (the longitudinal direction).

Before proceeding further, it is necessary to first examine the difference between the coiling and uncoiling of sheets and the cold bending of sheets into corners, in terms of both the physical process and theoretical modelling. Although both the coiling–uncoiling process and the cold bending of sheets into corners can be modelled as a problem of plane strain pure bending, the magnitudes of the bending curvatures involved in these two processes are different. According to the dimensions of typical cold-formed open sections given in the AISI Cold-Formed Steel Design Manual [14], the centre-line radius R_c of corners ranges from $2t$ to $6t$ (where t is the sheet thickness). These curvatures of corners are much greater than those produced by the coiling–uncoiling process. As indicated by Yu and Zhang [15], for pure bending of wide plates with the centre-line bending radius $R_c \geq 10t$, the use of engineering strains instead of logarithmic strains (or the so-called true strains) leads to a difference of less than 2.5% in the predicted maximum bending strain; that is, the use of engineering strains leads to sufficiently accurate results. However, for greater bending curvatures (i.e. $R_c < 10t$), logarithmic strains should be adopted in the analysis. Therefore, while engineering strains are used in the analytical solution for the coiling–uncoiling process, logarithmic strains are used in the present analytical solution for the cold bending of a sheet into corners.

Following Hill's general theory of sheet bending [16], in which the strains due to plane strain pure bending may be of any magnitude, the neutral surface of a wide sheet initially coincides with the middle surface, but moves towards the inner surface during the bending process. As a result, the fibres overtaken by the neutral surface are first strained in compression and then in tension. Such strain reversal happens over a zone bounded by the neutral surface and the deformed location of the original middle surface. Within this zone, there is a surface which is compressed and then extended by the same amount. This is known as the unstretched surface where the final strain is zero. Hill's general theory is applicable to the pure bending of wide sheets into both small and large curvatures. For bending into a small curvature such as $R_c \geq 10t$ [15], the zone of strain reversal is so small that it can be neglected, and the neutral surface can be assumed to coincide with the middle surface.

To extend the analytical solution for the coiling of a stainless steel sheet to model the cold bending of a sheet to form corners of large curvatures, the following simplifying assumptions are made: (1) the sheet thickness remains unchanged during cold