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Prediction of residual stresses and strains in cold-formed steel members

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Abstract

The objective of this paper is to provide an unambiguous mechanics-based prediction method for determination of initial residual stresses and effective plastic strains in cold-formed steel members. The method is founded on basic physical assumptions regarding plastic deformations and common industry practice in manufacturing. Sheet steel coiling and cross-section roll-forming are the manufacturing processes considered. The structural mechanics employed in the method are defined for each manufacturing stage and the end result is a series of closed-form algebraic equations for the prediction of residual stresses and strains. Prediction validity is evaluated with measured residual strains from existing experiments, and good agreement is shown. The primary motivation for the development of this method is to define the initial state of a cold-formed steel member for use in a subsequent nonlinear finite element analysis. The work also has impact on our present understanding of cold-work of forming effects in cold-formed steel members.

Keywords: Cold-formed steel; Residual stresses; Residual strains; Finite element analysis

1. Introduction

Thin cold-formed steel members begin as thick, molten, hot steel slabs. Each slab is typically hot-rolled, cold-reduced, and annealed before coiling and shipping the thin steel sheet to roll-forming producers [1]. Once at a plant, the sheet is unwound through a production line and plastically folded to form the final shape of a structural member, as shown in Fig. 1. This manufacturing process imparts residual stresses and plastic strains through the sheet thickness. These residual stresses and strains influence the load–displacement response and ultimate strength of cold-formed steel members.

In previous work, a statistical approach was employed to draw conclusions on the magnitude and distribution of longitudinal residual stresses using a data set of surface strain measurements collected by researchers between 1975 and 1997 [2]. The measured surface strains are converted to residual stresses using Hooke's Law and then distributed through the thickness as membrane (constant) and bending (linear variation) components. These residual stress distributions are a convenient way to express the measured residual surface strains, and are convenient as well for use in nonlinear finite element analyses, but they are not necessarily consistent with the underlying mechanics.

Plastic bending, followed by elastic springback, creates a nonlinear through-thickness residual stress distribution, in the direction of bending, as shown in Fig. 2 [3]. The presence of nonlinear residual stress distributions in cold-formed steel members has been confirmed in experiments [4] and in nonlinear finite element modeling of press-braking steel sheets [5]. A closed-form analytical prediction method for residual stresses and equivalent plastic strains from coiling, uncoiling, and mechanical flattening of sheet steel is presented in [6]. The same plastic bending that creates these residual stresses also initiates the cold-work of forming effect, where plastic strains increase the apparent yield stress in the steel sheet (and ultimate strength in some cases) as discussed in Ref. [7]. Together, these residual stresses and plastic strains comprise the initial material state of a cold-formed steel member.

A general method for predicting the manufacturing residual stresses and plastic strains in cold-formed steel members is proposed here. The procedure is founded on common industry manufacturing practices and basic

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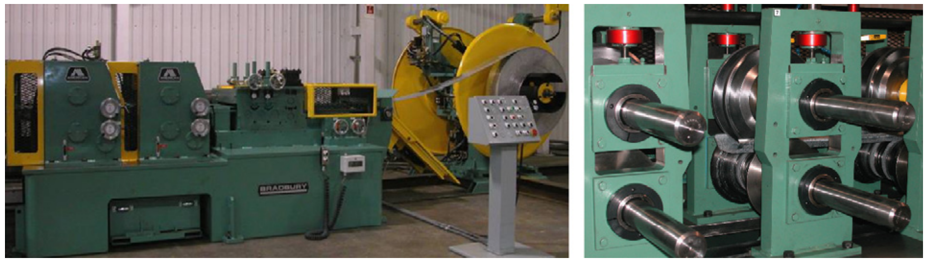

Fig. 1. Cold-formed steel roll-forming: (left) sheet coil enters roll-forming line, (right) steel sheet is cold-formed into C-shape cross-section (photos courtesy of Bradbury Group).

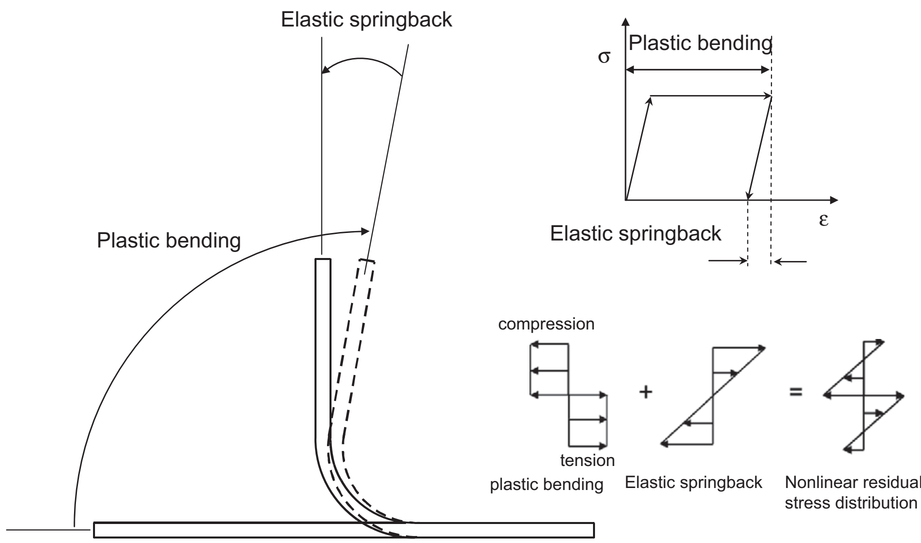

Fig. 2. Forming a bend: plastic bending and elastic springback of thin sheets results in a nonlinear through-thickness residual stress distribution.

physical assumptions. The primary motivation for the development of this method is to define the initial state of a cold-formed steel member for use in a subsequent non-linear finite element analysis. The derivation of the prediction method is provided for each manufacturing step, and the predictions are evaluated with measured residual strains from existing experiments. The end result of the method is intended to be accessible to a wide audience including manufacturers, design engineers, and the academic community.

2. Stress–strain coordinate system and notation

The stress–strain coordinate system and geometric notation used in the forthcoming derivations are defined in Fig. 3. The x-axis is referred to as the transverse direction and the z-axis as the longitudinal direction of a structural member. Cross-section elements are referred to as either 'corners' or 'flats'. The sign convention for stress and strain is positive for tension and negative for compression.

3. Prediction method assumptions

The following assumptions are employed to develop this prediction method:

(a) Plane sections remain plane before and after cold-forming of the sheet steel. This assumption permits the use of beam mechanics to derive prediction equations.

(b) The sheet thickness t remains constant before and after cold-forming of the sheet steel. A constant sheet thickness is expected after cold-bending if the bending is performed without applied tension [8]. Cross-section measurements demonstrate modest sheet thinning at the corners, where t in the corners is typically 5% less than in the flange and web [9]. This thinning is ignored here to simplify the derivations, although a reduced thickness based on the plastic strain calculations in Section 5 could be used if a higher level of accuracy is required.

(c) The sheet neutral axis remains constant before and after cross-section cold-forming. Theoretical models used in metal forming theory do predict a small shift in the through-thickness neutral axis towards the inside of the corner as the sheet plastifies [8]. This shift is calculated as 6% of the sheet thickness, t, when assuming a centerline corner radius, r_z, of $2.5t$. A neutral axis shift of similar magnitude has been observed in the nonlinear finite element model results for thin press-braked steel sheets [5]. This small shift is ignored here to simplify the derivations.