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Strength and ductility of corner materials in cold-formed stainless steel sections

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ABSTRACT

The cold work from the manufacturing process of cold-formed steel members can enhance the strength but reduce the ductility of materials. Due to a high cost of stainless steels, it is desirable to utilize this enhanced strength and avoid the early fracture in cold-formed stainless steel members. The paper is concerned with the prediction of the enhanced stress–strain behaviour and reduced ductility of corner materials in cold-formed stainless steel sections. The enhanced strength of corner materials has been traditionally determined using empirical models. However, most of these empirical models are only able to predict the enhanced 0.2% proof strength, but are neither capable of predicting the enhanced ultimate strength nor able to determine the reduced ductility. This paper first presents a modified weighted-average method for predicting the post-ultimate stress–strain behaviour and the fracture strain for stainless steels. An advanced numerical approach is next presented for predicting the full-range stress–strain behaviour of corner materials in cold-formed stainless steel sections, in which the modified weighted-average method is incorporated. The accuracy of this approach is demonstrated by comparing its predictions with test results. The proposed approach is generally applicable to cold-worked materials for predicting their enhanced strength, reduced ductility and full-range stress–strain behaviour. The proposed method and numerical results can explain why and how the ultimate strength of cold-formed steels can be increased and how the post-ultimate stress–strain behaviour can be utilized through cold working.

1. Introduction

Cold-formed steel members are usually manufactured by either roll forming or press braking. These forming processes can induce cold work in members and significantly change the mechanical behaviour of the material, including an increase in the strength and a reduction in the ductility. A large strength enhancement and a great reduction of ductility are usually found in the material in corners (or the so-called corner material). Many researchers have investigated the strength enhancement in the corner material of cold-formed steel sections [1–4] and cold-formed stainless steel sections [2–11]. Most of existing experimental studies [5,6,8,10] on the strength enhancement in stainless steel sections concerned mainly austenitic and ferritic grades, while some recent studies [2,3] covered various grades of stainless steels (i.e., austenitic, ferritic, duplex, and lean duplex grades) and carbon steels. The earliest experimental work for determining the corner properties of cold-formed steel sections was done by Karren [1]. He found that the method of forming had only little influence on the mechanical properties of corners, and proposed a semi-empirical equation for predicting the yield strength of corners in cold-formed carbon steel sections, which is a function of the corner radius and the mechanical properties of virgin steel sheets.

Due to a greater extent of strain hardening exhibited by stainless steel alloys than carbon steels, the strength enhancement in corners of cold-formed stainless steel sections has interested many researchers. Because of a high cost of stainless steels, it is desirable to not only utilize the enhanced strength but also avoid the early fracture arising from cold forming. On the other hand, the stress–strain relationship of corner materials would be needed in the geometrically and materially nonlinear analysis with imperfections (GMNIA) modelling for the buckling behaviour of cold-formed stainless steel members but less information on this relationship has been available as addressed by Greiner and Kettler [12]. Based on Karren's methodology [1], various empirical models for the prediction of the corner strength of stainless steel sections were proposed by different researchers [6,7,9,10]. Most of these existing empirical models [6,7,10] for stainless steel corners are only applicable to the prediction of the enhanced 0.2% proof stress, but are neither capable of predicting the enhanced ultimate strength nor able to predict the reduced ductility and full-range stress–strain behaviour of corner materials. The empirical model

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proposed by Ashraf et al. [9] is capable of predicting both the enhanced 0.2% proof stress and the enhanced ultimate strength of corner materials, but has not tackled the issue of the reduced ductility of corner materials in cold-formed stainless steel sections.

Accurate theoretical predictions of a complete stress–strain relationship of corner materials up to the fracture strain are needed for the advanced finite element (FE) analysis of cold-formed stainless steel structures and are not yet available. Nevertheless, the theoretical prediction and the numerical study of the enhanced 0.2% proof stress of stainless steel cold-worked materials can be found in Refs. [3,11] and Ref. [4] respectively, and some theoretical and numerical studies [13–18] have been attempted to predict the stress–strain relationship of flat metal strips after necking. However, in these existing studies [13–18], fracture strains were usually determined experimentally or using assumed values. A research team [11] at the University of Liège proposed a theory-based formula for the prediction of the enhanced 0.2% proof stress of stainless steel corner materials. In the theory-based formula [11], the enhanced 0.2% proof stress is calculated by considering a plastic strain offset of 0.2% plus the corner bending strain from the nominal stress–strain relationship of virgin stainless steel sheets. However, their method [11] cannot be used to predict the enhanced ultimate strength in corners as the maximum enhanced strength obtained from the formula is limited by the nominal ultimate strength of virgin sheets.

This paper is concerned with an accurate prediction of the enhanced stress–strain behaviour and reduced ductility of the corner material in cold-formed stainless steel sections by presenting an advanced numerical approach for the simulation of corner coupon tests. In the present paper, an analytical method, namely the modified weighted-average method, is first presented for predicting the full-range stress–strain behaviour of flat virgin strips up to the fracture strain. In this method, the fracture strain of virgin sheets can be determined analytically. An advanced numerical approach is then presented for predicting the reduced ductility and enhanced stress–strain behaviour of corner materials in cold-formed stainless steel sections, in which the modified weighted-average method is incorporated. In this approach, the effect of cold work from forming on the stress–strain behaviour of the corner material is taken into account accurately. The proposed approach can overcome the aforementioned difficulties and limitations encountered by existing empirical models [6–10].

2. Scope of work and terminology

In the present research, only two austenitic stainless steel grades 304 and 316L have been examined and considered. As the present paper deals with the theoretical and numerical modelling of the mechanical behaviour of thin-walled stainless steels, the failure process of metal strips in tension tests is first introduced in this section. In a uniaxial tension test of a flat metal strip, plastic instability and flow localization occur at the maximum load (i.e., the nominal ultimate stress) and the so-called diffuse necking starts (such as point U in Fig. 1) [15]. The diffuse necking occurs along the width direction and spreads over a length of the order of the width. At the end of diffuse necking, localized necking starts (such as point L in Fig. 1) and occurs with a through-thickness neck over a narrow band of the order of the sheet thickness, inclined at an angle to the specimen axis. The localized necking eventually leads to final fracture (such as point F in Fig. 1). Fig. 1 shows the typical nominal stress–strain curve of a flat tension specimen with a rectangular cross section. As shown in Fig. 1, the process from the onset of localized necking to fracture (such as the loading path L–F in Fig. 1) is often a very short and rapid process [15]. This two-stage necking process is illustrated in Fig. 2. The same necking process can also be found in the tension test of corner specimens in an experimental study reported in the next section. Fig. 3 shows the typical deformed shapes of a flat specimen and a corner specimen respectively after fracture.

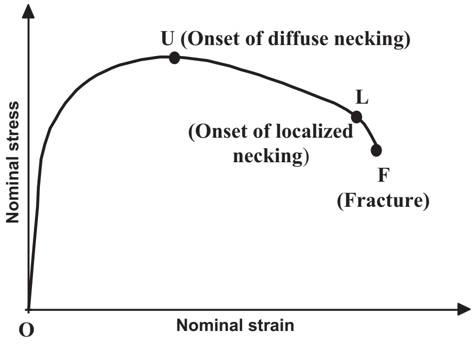

Fig. 1. Schematic plot of a typical nominal stress–strain curve for a flat tension specimen (reproduced from Ref. [15]).

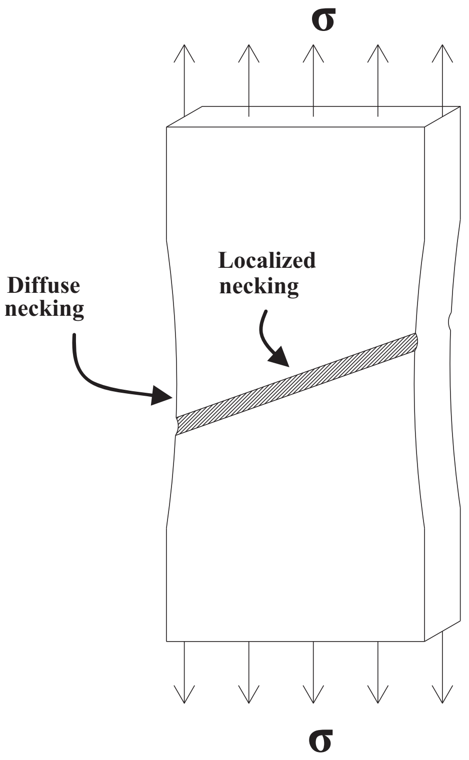

Fig. 2. Necking of a flat metal strip.

To verify the advanced numerical approach for capturing the aforementioned necking process, an experimental study on the mechanical properties of both virgin and corner materials of cold-formed stainless steel sections has been carried out and is first introduced in Section 3. The mechanical properties of flat sheets can be considered to represent the properties of virgin materials. In order to predict the enhanced strength and reduced ductility of corner materials numerically, a full-range stress–strain relationship of stainless steel sheets for strains up to fracture is required. The stress–strain relationship of stainless steels before diffuse necking can be easily defined by either laboratory testing or existing stress–strain models [19,20], but the method for determining the stress–strain relationship for strains after diffuse necking are not well defined. Therefore, the stress–strain relationship of flat sheets after diffuse necking (simply referred to as the post-ultimate stress–strain relationship hereafter) should be accurately defined first. To establish this relationship up to the fracture