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Full-field measurement of residual strains in cold bent steel plates

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ABSTRACT

With the recent American Association of State Highway and Transportation Officials bridge design code acceptance of cold bent fracture-critical and nonfracture-critical plates and the increasing use of cold bending by the bridge industry, there is a need to better understand and predict residual strains in cold bent steel. However, measuring residual strains is a challenging task since the bending process typically interferes with conventional instrumentation. This paper introduces three-dimensional Digital Image Correlation (DIC) as a new, non-destructive approach to measuring residual strains in cold bent steel that captures full-field strain data with high accuracy. DIC was used to measure residual strains in 18 cold bent 12.7 mm thick ASTM A36 steel plates, bent using a press-brake to a constant radius of 102 mm with varying angles (10, 20, and 30 degrees) and plate widths (76.2 mm and 203 mm). The measured residual strains are compared to analytical predictions and both two- and three-dimensional finite element models. A parametric study, using the validated finite element models, is completed for additional widths (12.7 mm and 140 mm) and thicknesses (6.35 mm and 19.1 mm) to investigate the effect of these parameters on circumferential strains, contact pressure, strain state, and to make modeling recommendations. Results are used to develop a means of predicting peak residual strains based on the final plate dimensions - a useful quality control measure.

1. Introduction

Understanding residual effects in cold bent steel is critical since the residual stresses and strains vary through the cross-sectional thickness, as opposed to residual effects from hot rolling for which there is little through-thickness variation. The variation in residual stresses is particularly important in building applications (in which thin-walled cold formed sections are typically used) as these affect a member's load-displacement behavior and ultimate strength due to early yielding at plate faces [1,2]. In the bridge industry (in which thick plates, including plates of built-up members, are typically bent) the primary concern is that strains induced from bending can result in cracking on the outer, tensile face of a bend as a result of the reduced ductility of plastically deformed steel (including the effect of strain aging) [3]. This reduction in ductility has been studied extensively and has been found to be related to the magnitude of plastic strain [4,5]. Due to this behavior, the bridge industry has significantly lagged behind the building industry in the implementation of cold formed steel [6] despite potential cost and time savings [7]. The American Association of State Highway and Transportation Officials (AASHTO)/National Steel Bridge Alliance (NSBA) *Steel Bridge Fabrication Guide Specifications* and the AASHTO *Load and Resistance Factor Design (LRFD) Bridge Construction Specifications* (up until a 2012 interim revision) did not permit cold-bending of fracture-critical steels and members [8–10]. However, based on the findings of Keating and Christian [8], the 2012 interim revision of AASHTO *LRFD Bridge Construction Specifications* has changed this stipulation such that fracture-critical and nonfracture-critical plates should be cold bent [11]. Through testing tensile steel samples at room temperature and subjected to heat conditions similar to that which would be used for heat-assisted bending of steel, Keating and Christian [8] found that cold bending is preferred over heat-assisted bending as the heat-assisted bending led to reduced ductility and contributed to cracking. They also found that strains exceeding 10% result in reduced fracture toughness through Charpy V-Notch tests [8]. This strain corresponds to a limiting bend radius of approximately 5t (where t is the plate thickness, using an analytical prediction for strain - see Eq. (3) and related discussion) which is the limit prescribed in the 2012 interim revision of AASHTO *LRFD Bridge Construction Specifications* [11].

Recent applications of cold bending in bridges include flanges of built-up girders to achieve a shallower cross-section (i.e., dapped girder) at supports [8,12], flanges of the Memorial Bridge between Portsmouth, NH and Kittery, ME (USA) to achieve a truss without gusset plates [13], and curved girder bridges [6,14–16]. Bent plates have also been used for connections of large skewed bridges [17]. With this new interest for bridge applications and recent changes to design code, this research is focused on understanding residual strains from cold bending

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steel plates. Measured residual strains are compared to existing analytical predictions and to both two- and three-dimensional (2D and 3D, hereafter) finite element (FE) numerical models. A parametric study, using the validated numerical models, is performed for additional widths [12.7 mm (0.5 in.) and 140 mm (5.5 in.)] and thicknesses [6.35 mm (0.25 in.) and 19.1 mm (0.75 in.)] to investigate the effect of these parameters on the circumferential strains, contact pressure, and strain state. These studies culminate in modeling recommendations to predict residual strains in a design environment. Furthermore, cold bending may occur in scenarios where the bend radius (a parameter used for predicting peak residual strains and the limiting metric used in AASHTO *LRFD Bridge Construction Specifications* [11]) is unknown or not clearly defined. This paper develops a means of predicting peak residual strains based on the post-bend plate dimensions. This is a useful quality control measure, as fabricators and contractors could readily determine if the residual strains exceed the 10% limit suggested by Keating and Christian [8].

Further, measuring residual strains in a laboratory environment is a challenging task since the bending process typically interferes with conventional instrumentation (e.g., strain gages). Surface strains can be measured by scribing a grid on the sample prior to bending then measuring distances between grid lines after bending as described by Brown and Jones [18] and as implemented by Sangdahl et al. [19], Karren [5], and Weng and White [20], among others. However, the gage length must be determined a priori. This length should be chosen to be sufficiently small so that local variations in strain can be observed and sufficiently large so that accuracy is not lost (here, accuracy is inversely related to the gage length) [18]. Furthermore, the accuracy of this approach is limited due to inaccuracies in the grid applications and inaccuracies in measuring the strains (which can be particularly challenging along curved surfaces) [18,19]. In addition to using a grid method, Weng and White [20] used high-elongation strain gages for tighter bend radii, with grooves cut into the dies to facilitate the gages and associated wiring. However, this method requires specially fabricated dies. Further, there is an extensive body of research focusing on the impact of cold-forming on material properties and behavior of members, including hollow structural sections (HSS, e.g., [21–23]), channels (C-shapes, e.g., [24–29]), angles (L-shapes, e.g., [30]), and hat-shaped sections (e.g., [24,28]). Note that this is a non-exhaustive review of this research.

This paper introduces 3D Digital Image Correlation (DIC) as a new approach to measuring residual strains in cold formed steel. DIC is a non-destructive, photographic measurement technique that captures full-field displacements and strains (see Subsection 4.2 for full description). DIC improves on the deficiencies of the grid method as the gage length can be adjusted during post-processing, it is capable of measuring displacements and strains around curves, and it offers higher accuracy. It improves upon strain gage methods which only provide data at distinct points (potentially missing a nearby high stress concentration), and cannot capture strain gradients [31]. This paper harnesses this full-field residual strain data to validate FE numerical models, compare with simplified analytical predictions, and ultimately develop a quality control measure for cold bending.

Table 1
Samples tested, including dimensions (Fig. 2). l = length prior to bending, θ = bend angle, w = width prior to bending, w_C = width of compressive face after bending, w_T = width of tensile face after bending, t = thickness prior to bending. Length and width measurements were made using a ruler with ±394 μm (0.01 in.) accuracy. Thickness measurements were made using a micrometer with ±2.54 μm (0.0001 in.) accuracy.

Sample	l (mm)	θ (deg)	w (mm)	w_C (mm)	w_T (mm)	t (mm)
1	432.9	10.21	76.20	77.15	75.84	12.35
2	433.5	10.19	76.28	77.14	75.76	12.46
3	431.4	10.19	76.20	77.52	75.87	12.37
4	433.9	9.174	201.0	201.5	200.5	12.42
5	432.7	9.193	201.3	201.6	200.3	12.33
6	434.0	9.365	201.3	201.7	200.6	12.43
7	484.2	19.61	76.75	77.90	76.21	12.38
8	483.4	19.63	76.37	77.69	76.02	12.37
9	483.3	19.33	76.20	77.04	75.49	12.32
10	482.7	18.85	200.8	201.6	200.0	12.43
11	483.9	18.76	200.8	201.2	199.7	12.41
12	483.4	18.84	201.0	201.3	200.0	12.43
13	530.4	29.61	75.44	76.68	74.69	12.33
14	533.2	29.63	76.37	77.52	75.62	12.40
15	530.7	29.94	75.44	77.08	74.88	12.42
16	531.9	28.98	201.3	201.3	199.8	12.45
17	533.9	28.82	201.1	201.5	199.8	12.40
18	531.5	29.01	201.0	201.4	199.5	12.46

2. Objectives and scope

The objective of this research is to study full-field residual strains induced from cold bending. The full-field behavior of 18 [12.7 mm (0.5 in.)] thick ASTM A36 steel plates (Table 1), bent using a press-brake (Figs. 1 and 2) to a constant radius (r) of 102 mm (4.0 in.) with varying angles (θ = 10°, 20°, and 30°), is measured experimentally using 3D DIC. Measured results are compared to analytical predictions and with both 2D and 3D FE numerical models, culminating in

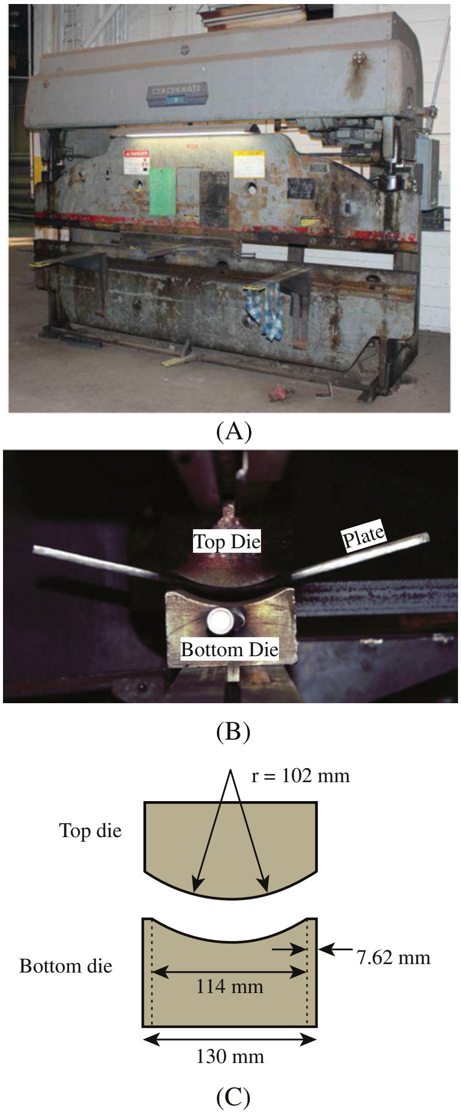

Fig. 1. Press brake used for bending, including (A) photograph of press brake, (B) photograph of press brake as specimen is being bent, and (C) rendering of top and bottom dies, including dimensions.