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Curving structural steel girders by two-point bending

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ABSTRACT

Point bending is often used for cambering and curving steel girders to large radii. In this method, a fabricated straight girder is bent by concentrated loads applied at the third points using hydraulic jacks. The required geometric profile develops from permanent residual deformations induced upon removing the loads. The resulting shape is not circular but closer to a parabolic shape. The goal of this paper is to evaluate the profiles of structural steel girders curved by point bending in the post-yield range and explore alternative loading configurations that result in the fabrication of specimens that better approximate circular curves. Limits are developed on the minimum radius of curvature that can be achieved to ensure accuracy of the idealization and on the induced strain to avoid damaging the steel section or adversely affecting the physical properties of steel. The accuracy of the proposed analysis is established by comparing predictions against available experimental results from a full-scale test. Further validation is also provided based on comparisons with results from 3-D finite element analysis incorporating initial residual stresses and geometric imperfections.

1. Introduction

Cold bending uses loads to induce circular curves in steel girders for structural and architectural applications. Fabricators prefer this method since it is more efficient, less time consuming, allows better control over geometry and yields more consistent outcomes than heat curving.

Several cold bending methods are available and their use depends on girder size, radius requirement and end application of the material [1]. Rolling is used to curve steel to a tight radius by continuously feeding it between three or more rollers [2]. Point bending or gag pressing is customarily used for cambering or curving to larger radii by applying a concentrated force at the middle or at the girder third points. Draw bending is recommended for complicated bends [2] where a steel member is rotated around a die.

Literature review shows that modelling and simulation of the roller bending process was previously performed and compared with experimental results [3,4]. In contrast, research on point bending (Fig. 1) has only been limited to theoretical studies relating to cambering and curving applications [5,6]. This paper extends this research to validate theoretical point bending solutions for inducing horizontal curves by comparing predictions against experimental results obtained from full-scale testing and from 3-D finite element modelling. The intent is to explore the applicability and practical implementation of the point bending process for fabricating circular profiles.

Findings from this paper provide insights into the geometric and material non-linearity of steel under point bending that can lead to improvement of the process. The optimal load set-up is one that best approximates a circular curve (Fig. 2) without damaging the steel section or affecting its toughness or ductility.

2. Background and objectives

The point bending procedure developed earlier derived closed-form expressions for residual deformation and curvature for curving and cambering based on plastification of steel [5,6]. In curving, the girder is bent about its weak axis while in cambering it is bent about its strong axis.

The accuracy of the theoretical solution was verified by comparing mid-length residual deformation (Δ_{res}) (Fig. 2) with the ordinate of a circular curve. In this paper, this validation is extended by comparing results at different points along the girder length. Additionally analytical predictions are compared against experimental results obtained from full-scale testing and 3-D finite element modelling.

The outline of the paper is as follows:

a) derive closed form solutions relating load to deformation at any point along the beam length and not just at midspan.
b) identify the key parameters and present the solutions in a parametric form to simplify mathematical computations.
c) develop plots to show the variation of induced deformations as a function of the key parameters for conventional steel grades.
d) perform a parametric analysis to identify the sensitivity of varying the parameters on induced deformations and radius of curvature.
e) set limits on the loads' magnitude and spacing so that the steel girder is not over-strained and its tensile and yield strength are not adversely affected.

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Nomenclature

a'	offset of point load from end supports
b	overhang dimension
b_f	flange width
E	modulus of elasticity
f_y	yield stress
I	weak axis moment of inertia
L	girder length between end supports
L'	total girder length
M	bending moment
P	point load magnitude
P_{flange}	point load per flange
R	radius of curvature
t_f	flange thickness
t_w	web thickness
x	offset along girder length
x_2	onset of yield
y_y	depth of elastic core
α	offset parameter (x/L)
χ	onset of yield parameter (x_2/a')
η	multiple of the yield strain ε_y
$(\delta_e)_x$	elastic deformation at offset x
$(\delta_p)_x$	inelastic deformation at offset x
$(\delta_{res})_x$	residual deformation at offset x
δ_x	ordinate of the circular curve at offset x
Δ_{res}	midspan ordinate
Δ_p	inelastic deformation at midspan
ε	residual strain
ε_{max}	maximum loading strain
ε_y	yield strain
σ	stress
τ	load offset parameter (a'/L)

f) present a formalized procedure for determining the optimal load set-up for curving a steel rolled profile to a radius of curvature R.

g) validate the procedure based on comparisons with experimental results and 3-D finite element analysis.

3. Description of the point bending operation

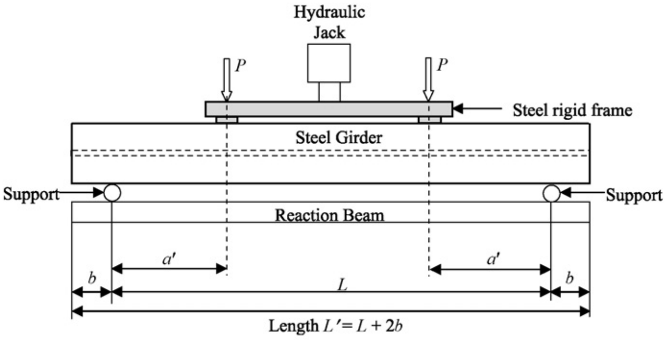
Point bending systems used to curve steel girders are usually proprietary [7]. A typical set-up for curving (weak axis bending) is shown in Fig. 1a. The load is applied in a single step by a hydraulic jack and is distributed by a rigid frame to two equidistant points distant a' from the supports. To avoid localized damage to the flanges, steel distribution plates or channels are used at the point loads and rollers at the reaction supports (Fig. 1b). The actual loading frame used in the experimental study is shown later in Section 8.2.

3.1. Girder geometry

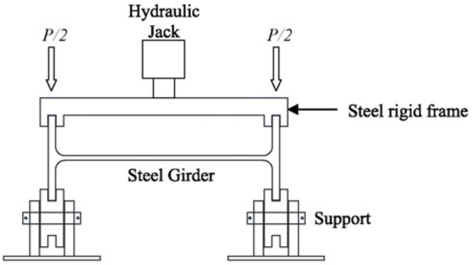
The length of the straight fabricated steel girder between supports is designated as L. The actual length L' is longer to satisfy placement requirements within the loading frame. This is defined as $L' = L + 2b$, where b is the overhang at each end support (Fig. 1a). Dimension b is usually set at $0.05L$ so that $L' \approx 1.1L$; the overhang length is trimmed after the cold curving operation is completed [6].

3.2. Idealization of curve

Typically loads are positioned at the third points of the girder ($a' = L/3$, Fig. 1a) and the deformed shape is close to a smooth curve [2]. One of the objectives of this paper is to explore the accuracy of the point bending operation for different loading configurations. For this purpose, closed form expressions for deformation are re-written as a function of the point load position a'. This allows the relationship between the load position and deformed shape to be assessed theoretically.



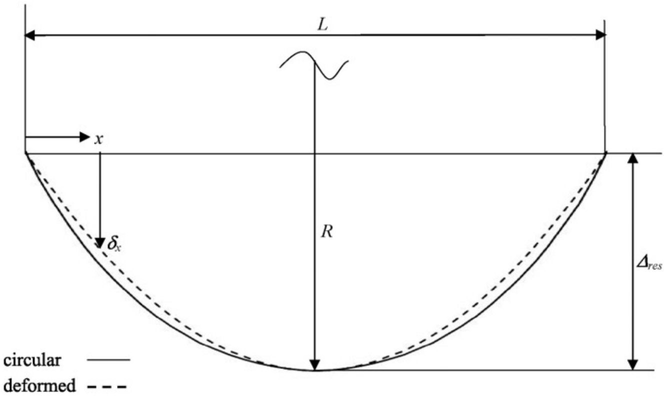
(a) Elevation View



(b) Side View

Fig. 1. Point bending set-up (weak axis bending shown).

For a curved beam of radius of curvature R, the midspan ordinate (Δ_{res}) corresponding to the maximum induced deformation is the key variable. Fig. 2 shows the equation for the ordinate of a circular curve (δ_x) at distance x along the girder length L. The accuracy of the bending operation relies on a close match between the circular curve and the permanent deformed shape due to bending. It is shown later that the deformation equations are polynomials of higher order and that accuracy of the point bending operation depends on the span length to radius of curvature ratio (L/R) (agreement is better for $L/R \le 0.5$). The analysis will identify ranges of parameters for which the deformed shape better approximates a circular curve.



$$\delta_x = \sqrt{R^2 - \left(x - \frac{L}{2}\right)^2} - \sqrt{R^2 - \frac{L^2}{4}}\;;\; \Delta_{res} = R - \sqrt{R^2 - \frac{L^2}{4}}\ @\ x = L/2$$

Fig. 2. Circular shape versus deformed shape.