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Numerical analysis of heat-curved I-girders

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ABSTRACT

Heat curving is a practical and economical process used by steel fabricators for curving structural steel. In this method, the flange edges of a fabricated straight girder are asymmetrically heated to induce residual curvature on cooling. Available analytical methods for predicting the resulting residual stress, strain and curvature are complex and iterative because of the need to account for material and geometric non-linearity. This paper presents a single-step, non-iterative, numerical procedure for determining the effects of heat-curving on residual stress and strain based on a previously developed simplified analysis. Thermal equilibrium equations for idealized heating profiles are first recast in a general parametric form and then solved numerically for standard heating width and temperature using modern technical computing. The resulting solutions are expressed as polynomial functions to allow the solution space for the residual curvature to be graphically represented. Curvature predictions using this simplified approach are shown to be within 11% of measured values and within 5% of values obtained using more rigorous numerical methods.

1. Introduction

Heat-curving is a trial and error method commonly used for fabricating curved structural steel shapes (Brockenbrough, 1970a). In the process, both flange edges on one side of a fabricated straight girder are heated in a precise manner to induce uneven expansion and contraction that results in the development of the required curvature upon cooling (Brockenbrough, 1968), Fig. 1. The heating profile is non-uniform and varies along the heated width as shown in Fig. 2 (Brockenbrough, 1970b). Numerical modelling is complicated at high temperatures due to yielding of the steel section and the dependence of steel's strength and stiffness on temperature shown in Fig. 3. This makes the analysis highly non-linear for determining strains and corresponding curvatures (Brockenbrough, 1970a).

In a recent study (Gergess & Sen, 2003), the authors presented a simplified Duhamel analogy-based method for analysing heat-curved I-shaped steel girders (Brockenbrough, 1968, 1970a). It used an average centroidal temperature for an idealized temperature distribution (Fig. 4) to calculate the yield stress, modulus of elasticity and coefficient of thermal expansion. This assumption permitted the derivation of closed-form equations for thermal stress and strain as a function of the heating temperature T, heated width h_a and girder cross-sectional properties (flange thickness t_f and width b_f, web depth d and thickness t_w, Fig. 2). As a result, residual curvature could be calculated in a single-step without the need for iterations that is the signature of all non-linear analysis.

This paper further extends the simplified method by using Wolfram Mathematica V.9.0 algebra package to conduct the numerical analysis. The governing equations were cast in parametric form and the algebra package was used to express solutions as polynomial functions for the practical range of values of the heated width h_a and heating temperature T (Fig. 2). This representation allowed the creation of contour plots displaying the relationship between the parameters needed to calculate residual curvature. Accuracy of the proposed analysis is verified by comparison with available theoretical results (Brockenbrough, 1970a) and experimental results (Brockenbrough, 1970b) for different heating widths and temperatures.

2. Background

In the late 1960s the then US Steel Corporation initiated a major experimental study to investigate heat curving. Several papers

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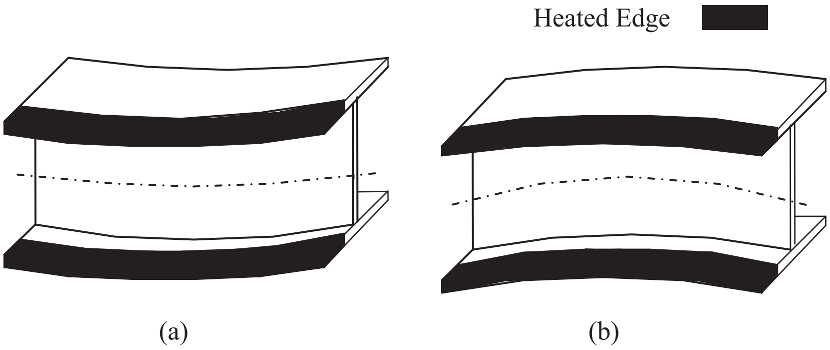

Fig. 1. Isometric view of a heat-curved steel I-girder subjected to continuous heat (a) during heating, (b) after cooling.

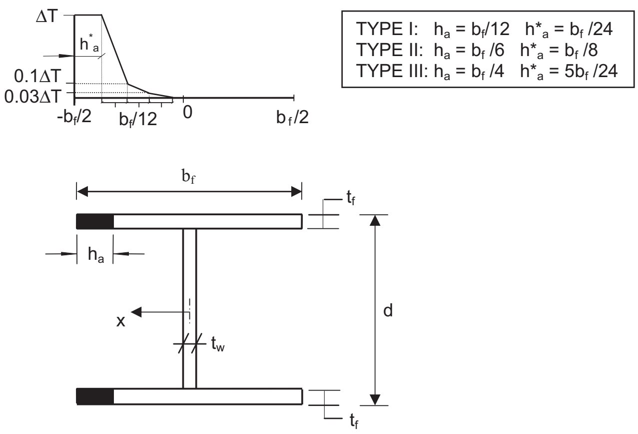

Fig. 2. Heating profile and temperature distribution.

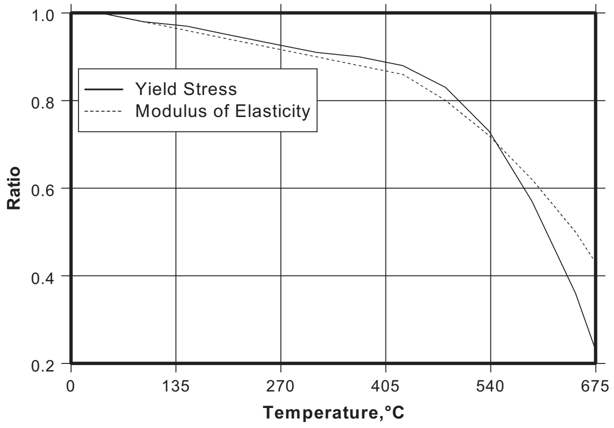

Fig. 3. Normalized temperature-dependent steel properties, $(F_y)_T/F_y$, E_T/E.

resulted from the study (Brockenbrough, 1968, 1970a, 1970b, 1970c, 1972, 1973) that constitute the basis of the AASHTO specifications (AASHTO, 2008) still in use.

2.1. Heating profile

In heat-curving heat can be applied continuously (Brockenbrough, 1972) or intermittently (V-heating) (Brockenbrough, 1973). Generally, V-heating is used for larger radii. For continuous heat, the heated width h_a varies from one twelfth to one fourth the flange width ($b_f/12$–$b_f/4$, Fig. 2), depending on the tightness of the curvature required (Brockenbrough, 1970a, 1972). Larger heated widths result in larger curvature (e.g. smaller radii). This paper focuses on applications using continuous heat applied simultaneously to the top and bottom flanges.

Numerical analysis requires information on the temperature profile and its variation over the width of the flange. Fig. 2 shows that the temperature distribution for a heating temperature T applied over a width h_a is constant over a somewhat smaller distance h_a^* then transitions linearly over widths ($b_f/12$) to the ambient temperature T_0 outside the heated width. This distribution was established from a theoretical solution for a semi-infinite thin plate with a moving point heat source along its edge (Myers, Vyehars, & Borman, 1967).

Heating protocols that result in temperatures greater than 675 °C are considered destructive leading to rejection of the steel (New York State Steel Construction Manual, 2008). For this reason the maximum temperature is conservatively set by AASHTO (AASHTO, 2008) as 621 °C for conventional steel grades. Temperature differential is denoted by $\Delta T = (T - T_0)$ in Fig. 2.

2.2. Steel properties variation with temperature

Over the temperature range permitted for heat-curving ($\leq$621 °C), the mechanical properties of steel (yield stress F_y, modulus of elasticity E, coefficient of thermal expansion α) reduce significantly (Brockenbrough, 1970a). Equations for material properties normalized with respect to the ambient temperature are available (Brockenbrough, 1968, 1970a). They are plotted in Fig. 3 (the yield stress is designated as $(F_y)_T$ and the modulus of elasticity as E_T at heating temperature T). The increase in the coefficient of thermal expansion α_T is given by Eq. (1) as a function of T (°C) (Brockenbrough, 1970a):

$$\alpha_T = (1.10916 + 0.0006156T)10^{-5} \quad 38\,^{\circ}\mathrm{C} < T < 621\,^{\circ}\mathrm{C} \tag{1}$$

2.3. Duhamel analogy

Numerical solutions for heat-curving are based on a two-dimensional superposition-based thermal load analysis known as the Duhamel analogy (Brockenbrough, 1970a; Gergess & Sen, 2015). Since no external forces or restraints are applied during heat curving, internal thermal stresses are self-equilibrating. Stability is assured by supporting the girder at mid-length during the operation (Brockenbrough, 1970b). This frees the girder to deform since the mid-length support location corresponds to the plane of zero movement.

The Duhamel analogy assumes that the flange plate is composed of a series of longitudinal strips that are initially allowed