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Tangent moduli of hot-rolled I-shaped axial members considering various residual stress distributions

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ABSTRACT

This paper presents an equation for the effective tangent moduli for steel axial members of hot-rolled I-shaped section subjected to various residual stress distributions. Because of the existence of residual stresses, the cross section yields gradually even when the member is subjected to uniform axial stresses. In the elasto-plastic stage, the structural response can be easily traced using rational tangent modulus of the member. In this study, the equations for rational tangent moduli for hot-rolled I-shaped steel members in the elasto-plastic stage were derived based on the general principle of force-equilibrium. For practical purpose, the equations for the tangent modulus were presented for conventional patterns of the residual stress distribution of hot-rolled I-shaped steel members. Through a series of material nonlinear analyses for steel axial members modeled by shell elements, the derived equations were numerically verified, and the presented equations were compared with the CRC tangent modulus equation, the most frequently used equation so far. The comparative study shows that the presented equations are extremely effective for accurately analyzing elasto-plastic behavior of the axially loaded members in a simple manner without using complex shell element models.

1. Introduction

In general, hot-rolled steel members are not free from residual stresses distributed in various patterns owing to the characteristics of the manufacturing method. The existence of residual stresses may induce gradual yielding in the section of steel members even when external axial loads are applied. To predict the elasto-plastic response in the gradual yield stage of the axially loaded steel members, the tangent modulus has been widely used for its simplicity. The CRC (Column Research Council) tangent modulus suggested by Galambos [1] has been the most widely used one. In particular, the modulus was used in the plastic hinge method and refined plastic hinge method to consider gradual yielding of the I-shaped member that has specific residual stress distributions by Chen and Lui [2], Liew et al. [3], Chen and Liew [4], Kim and Chen [5], Kim et al. [6], Kim et al. [7], and Kim [8].

But the CRC tangent modulus, which was basically derived via Euler's elastic buckling equation with assumption of constant maximum compressive residual stress, has limitations in applicability where different various residual stress distributions are to be considered. As shown in Eq. (1), various effective factors, such as maximum residual stress values, patterns and the sectional shapes of members, cannot be considered in the CRC tangent modulus.

$$E_t = 1.0E \quad P \le 0.5P_y \tag{1}$$

$$E_t = 4\frac{P}{P_y}E\left(1-\frac{P}{P_y}\right) \quad P \ge 0.5P_y \tag{2}$$

In this study, rational new tangent moduli are derived based on the general principle of force-equilibrium. First of all, the linear residual stress distributions suggested by Galambos and Ketter [9], and by ECCS [10], respectively, are considered as the general residual stress patterns of hot-rolled steel members. In addition, the parabolic stress distribution suggested by Szali and Papp [11] is also taken into account. Including the effect of the maximum or minimum residual stress value, the presented equations for the tangent moduli produce clearer and more accurate computation of the elasto-plastic behavior. The derived equations are verified based on the results of nonlinear finite element analyses for axially loaded steel members modeled by shell elements with residual stress distributions aforementioned. The accuracy and the verification of the presented tangent modulus equations are evidently shown by comparing the load–displacement curves of nonlinear finite element analyses with those of present study (Fig. 1).

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Nomenclature

A	cross-sectional area
A^*	elastic cross-sectional area
b	width of flanges
E	elastic modulus
E_t	tangent modulus
Δf	additional axial stress
f_y	yield stress
$f(y)$	axial stress function at the flanges of the I-shaped member with parabolic residual stress distribution
$f(z)$	axial stress function at the web of the I-shaped member with parabolic residual stress distribution
g	coefficient of maximum tensile residual stress
h	height of a web
h_0	net height of a web
L	length of an axial member
P	applied axial force
ΔP	additional axial force
P_t	applied total axial force
P_y	yield axial force
r	coefficient of maximum compressive residual stress at flanges
r'	coefficient of maximum compressive residual stress at a web
t_f	thickness of flanges
t_w	thickness of a web
υ	Poisson's ratio
x_f	length parameter of yield area at flanges
x_w	length parameter of yield area at a web

2. Residual stresses of hot-rolled I-shaped steel members

Based on the principle of force equilibrium, the resultant forces in the section of a member that has specific residual stress distribution should vanish where no external force is applied. As shown in Fig. 2, the residual stress distributions are generally classified into two categories, linear and parabolic distributions (Fig. 3).

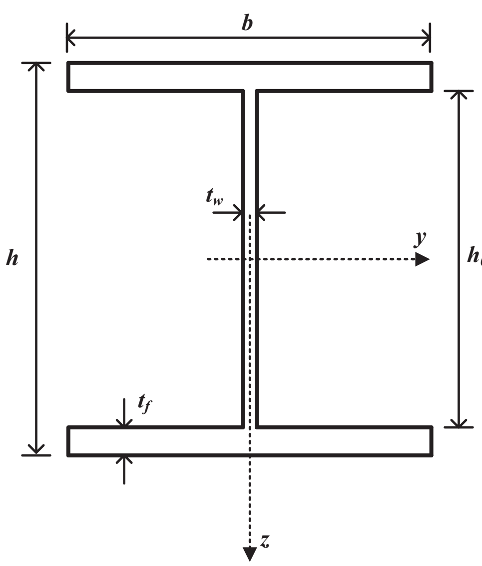

Fig. 1. Simplified cross section of an I-shaped steel member.

First of all, the parabolic distribution suggested by Young is based on an experimental study. Eqs. (3)–(5) show the maximum and minimum residual stresses of the distribution. As shown in the equations, the residual stress distribution is determined by the sectional dimension parameters, such as height, width and thickness of flange and web. Meanwhile, it should be noted that different steel grades are not taken into account in determining the residual stress distribution using the following equations:

$$f_{cf} = -165\left(1 - \frac{ht_w}{2.4bt_f}\right) \tag{3}$$

$$f_{cw} = -100\left(1.5 - \frac{ht_w}{2.4bt_f}\right) \tag{4}$$

$$f_t = 100\left(0.7 - \frac{ht_w}{2bt_f}\right) \tag{5}$$

where, f_{cf} and f_{cw} are maximum compressive residual stresses at the flanges and web, respectively, and f_t is the maximum tensile residual stress at the junctions of the flanges and web; the units are N/mm^2.

The other parabolic distribution suggested by Szalai and Papp [11] was derived by satisfying all equilibrium equations, including torsional and warping effects. As shown in Eqs. (6)–(11), the functions of residual stress distribution are determined by the steel grade as well as by sectional dimension parameters.

$$f(y) = c_f + a_f y^2 \tag{6}$$

$$w(z) = c_w + a_w z^2 \tag{7}$$

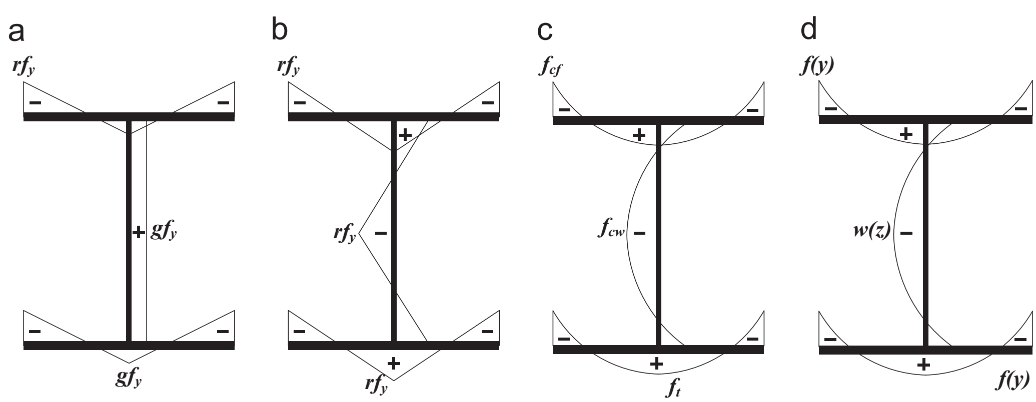

Fig. 2. General residual stress distributions: (A) linear (Galambos and Ketter [9]), (B) linear (ECCS [10]) (C) parabolic (Young [12]), and (D) parabolic (Szalai and Papp [11]).