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Method for Reducing Warping Stresses in Torsionally Loaded I-Section Members using CFRP Plates

Mamadou Konate and Zia Razzaq

***Abstract* — This paper presents a method for reducing warping normal stresses in torsionally loaded I-section members by utilizing carbon fiber-reinforced polymer (CFRP) plates. The CFRP plates are bonded to the outer surfaces of the flanges with a view to reducing warping normal stresses. The maximum warping normal stress in the flanges of a steel I-shaped member without the CFRP plates is compared to those obtained with the CFRP plates having various thicknesses. It has been found that the use of CFRP plates bonded to both flanges of the I-section result in a substantial reduction of the warping stresses. For the study presented, the maximum warping normal stress without CFRP plates drops down to merely one-third of its value when 0.625-in. thick CFRP plates are mounted on the outer surfaces of the I-section flanges.**

***Keywords* — Carbon Fiber Reinforced Polymer, Steel I-Section, Torsional Loading, Warping Stresses Reduction.**

I. INTRODUCTION

In 1940, Vlasov [1] published a collection of his pioneering works on thin-walled beams which included warping deformations associated with both applied and induced torsion. Although Vlasov theory has been applied to thin-walled structural members found in buildings, aircrafts, naval, and other structures [2], there is a need for methods for reducing warping stresses developed due to torsional loading. Kabir and Seif [3] have conducted a lateral-torsional stability study of steel I-beams retrofitted with fiber reinforced polymer materials. Lee and Kim [4] investigated the lateral-torsional buckling response of thin-walled laminated channel-section beams. Both of these studies involved second-order induced torsional effects. References 5 and 6 illustrate that the warping normal stresses in an I-shaped section under applied torsion can be quite large. The current paper is focused on investigating the effectiveness of a method of using CFRP plates in regions of high warping normal stresses in steel I-section members with a goal of reducing such stresses.

II. PROBLEM DEFINITION

The problem posed herein is the determination of the effectiveness of using CFRP plates to reduce warping normal stresses in an I-shaped steel member when subjected to an applied torsional moment. Although the method is illustrated for a particular type of an application, it is fairly general and can be applied to other types of thin-walled open section members such as a T-section, channel section, Z-section, and built-up open members with various types of torsional loading and boundary conditions. Fig. 1 shows the schematic of a typical steel I-shaped member of length L with CFRP plates bonded to the outer surfaces of the upper and lower flanges along the entire length of the member. A concentrated torsional moment M is applied to the member at its midspan. The member has torsionally pinned boundary conditions. This means that although the member ends can warp freely, they are restrained from developing any torsional rotations at the ends. Fig. 2 shows the member cross-section in which d is the steel section depth, b_f is the flange width, t_f is the steel section flange thickness, t_w is the steel section web thickens, and t' is the thickness of each CFRP plate. The reason for bonding the CFRP plates to the flanges is because that is where the largest warping stresses develop.

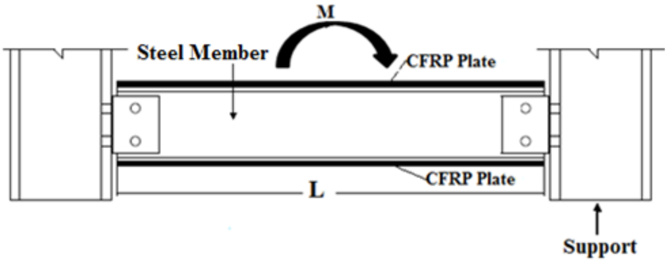

Fig. 1. Torsionally loaded steel I-section member with CFRP plates bonded at top and bottom.

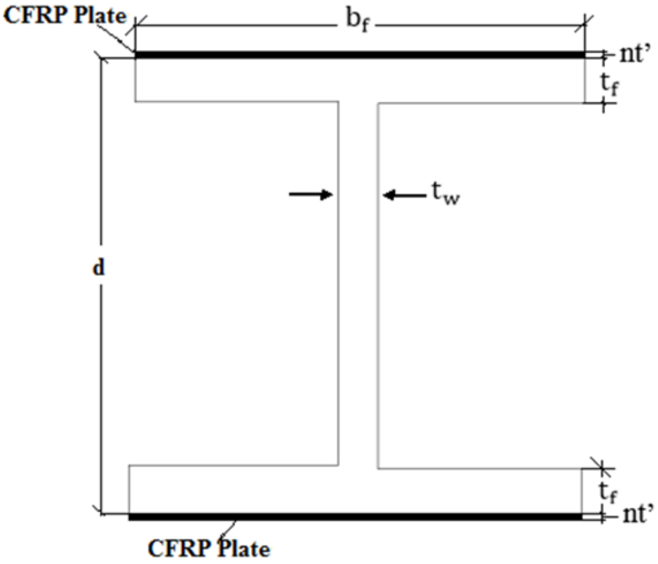

Fig. 2. Steel I-section with CFRP plates.

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III. Warping Stresses Including CFRP

The analysis is based on transforming CFRP plate thickness to equivalent steel by using the modular ratio expression given in (1):

$$n = \frac{\mathrm{E_{CFRP}}}{\mathrm{E_s}} \qquad (1)$$

In this equation, $\mathrm{E_{CFRP}}$ and $\mathrm{E_s}$ are the elastic modulus values of the CFRP plate material and steel taken respectively as 22,000 ksi and 29,000 ksi. The shear modulus, G, for steel is 11,200 ksi. The problem is to theoretically predict the maximum warping normal stress versus the CFRP plate thickness relationship for the torsionally loaded member in order to evaluate the effectiveness of the CFRP plates. The warping normal stress is maximum at the flange tips of an I-shaped cross-section [1], [2], [5] and develops at the midspan of the member and is given by (2) as follows:

$$\sigma_w = E\omega_n \phi'' \qquad (2)$$

in which ω_n is the normalized unit warping modified herein to account for the presence of CFRP plates as given by the following expression given in (3):

$$\omega_n = \frac{d' b_f}{4} \qquad (3)$$

The presence of CFRP is incorporated in the average section depth d' based on the following expression given in (4):

$$d' = d - t_f + nt' \qquad (4)$$

in which nt' is the CFRP plate thickness transformed into equivalent steel. The term ϕ'' in (2) is the second derivative of the twist angle ϕ [5] which is given by the following expression given in (5):

$$\phi = A + B\cosh kz + C\sinh kz + \frac{Mz}{k^2 EI_\omega} \qquad (5)$$

in which z is the member longitudinal axis with its origin at the member left end, and A, B, and C are constants of integration found using the following boundary and symmetry conditions (6):

$$\phi(0) = \phi''(0) = \phi'(L/2) \qquad (6)$$

The term k is found using the following expression given in (7):

$$k^2 = \frac{GK_T}{EI_\omega} \qquad (7)$$

in which K_T is the St. Venant torsional constant [5], [6] given in (8):

$$K_T = \frac{1}{3}\,\Sigma b_i t_i^3 \qquad (8)$$

In (8), the summation is for the number of plates making up the cross-section. The I-section including the CFRP plates bonded to the flanges has a total of three parts in which the flange plates include the equivalent or transformed area of the CFRP plates. Consequently, the cross-sectional plate widths in Equation (8) are $b_1 = b_f$; $b_2 = (d - 2t_f)$; $b_3 = b_f$; and the plate thicknesses are $t_1 = t'$; $t_2 = t_w$; and $t_3 = t'$.

The warping moment of inertia I_ω given in Reference 5 is modified herein to account for CFRP plates and is given as follows in (9):

$$I_\omega = 0.25 I_y\, (d')2 \qquad (9)$$

in which I_y is the moment of inertia of the cross section about its minor principal axis of the cross section including both the steel section as well as the transformed CFRP plates.

IV. Numerical Results

Using the analysis presented in Section III of this paper, a numerical study is conducted for an I-section member with the type of torsional loading shown in Fig. 1. The curve in Fig. 3 shows the relationship between the maximum warping normal flange stress versus CFRP plate thickness for a W10x49 steel member with CFRP plates mounted as shown in Fig. 1 and Fig. 2. The cross-sectional flexural and warping properties of the W10x49 section are given in Reference 7 and are used herein. In the present study, a torsional moment M of magnitude 54.0 kip-in. is used. The warping normal stress value at the flange tips for zero CFRP plate thickness, and for various CFRP plate thicknesses, namely, t' = 0.125 in., 0.25 in., 0.375 in., 0.5 in., and 0.625 in. are plotted in Fig. 3. To generate this curve, the values for d, b_f, t_f, t_w, and L are taken as 10.0 in., 10.0 in., 0.56 in., 0.34 in., and 180 in., respectively. The results in this curve show a very substantial reduction in warping stress as the thickness of the CFRP plates increases. Based on a comparison with the warping stress with no CFRP plates, the reduction in the warping stress due to the addition of the CFRP plates is found to be quite substantial and dependent on the thickness of the plates. With t' = 0.625 in., the warping stress is almost one-third the value with no CFRP plates. Other values are found to be between these two limits.

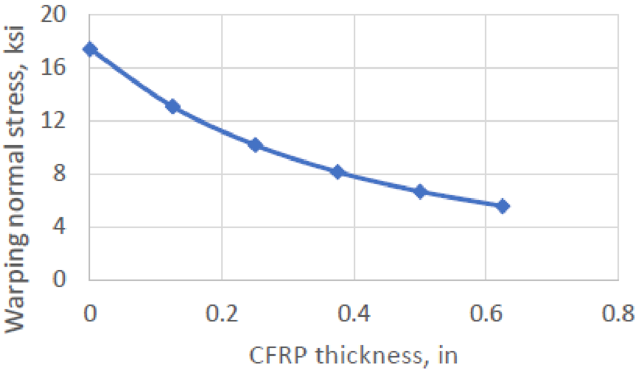

Fig. 3. Warping normal stress versus CRRP plate thickness.

V. Conclusions

The use of CFRP plates on the I-section member under torsion is found to be quite effective for reducing the warping normal stresses. A comparison of the maximum warping normal stresses in the flanges of a torsionally pinned I-section steel member without CFRP plates is made to those obtained with CFRP plates of various thicknesses. The numerical study presented for the type of loading and boundary conditions used shows a very significant reduction in the warping stresses in the flanges of the steel I-section when CFRP plates are used. Results show that the percent warping normal stress decreases with an increase in the thickness of the CFRP plates. For the study presented, the maximum warping normal stress without CFRP plates drops down to merely one-third of its value when 0.625-in. thick CFRP plates are mounted on the outer surfaces of the I-section flanges.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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