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Lateral torsional buckling of STEEL beams strengthened with GFRP plate

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ABSTRACT

The present study investigates the lateral-torsional buckling of wide flange steel members strengthened by a Glass Fiber Reinforced Polymer (GFRP) plate bonded to one of the flanges through an adhesive layer. A variational formulation and two finite elements are developed for the problem. The formulation captures global and local warping effects, shear deformation due to bending and twist, and partial interaction between the steel and GFRP provided by the flexible layer of adhesive. The destabilizing effects due to strong axis bending, axial force and load height effect are incorporated into the formulation. The first element involves two nodes and 16 buckling degrees of freedom (DOFs) while the second element involves three nodes and 14 DOFs. Comparisons of present model results against those based on 3D finite element analysis based on solid elements demonstrate the ability of the present models to accurately predict the buckling loads and mode shapes at a fraction of the modelling and computational efforts. Practical examples quantify the gain in elastic buckling strength achieved by GFRP strengthening, and characterize the moment gradient factors and load height effects. Elastic buckling interaction diagrams are developed for beam-columns and comparisons are provided to interaction diagrams of un-strengthened beams.

1. Introduction

GFRP is a lightweight, durable, and economic material that can be formed into thick plates capable of resisting tensile, shear and compression stresses [1]. Strengthening existing steel structures using adhesively bonded GFRP plates has become a viable option in recent years given the advantages it offers; when compared to traditional strengthening methods using either welded- or bolted-steel plates [2], GFRP installation is relatively easier and faster. When compared to bonded carbon-FRP (CFRP) plates with relatively high elasticity modulus [3,4], GFRP plates possess a lower stiffness. However, this drawback can be compensated for by using thicker plates [1]. This provides the added advantage of achieving a higher flexural stiffness compared to stiffer but thinner CFRP plates and thus can be advantageous when strengthening thin compression flanges to increase their local and global buckling strengths [5,6]. Additionally, when in contact with steel, GFRP do not induce galvanic corrosion.

Strengthening applications involving GFRP plates were investigated in a number of studies. El Damatty et al. [1] conducted an experimental study for W-shaped steel beams strengthened with GFRP plate bonded to the tensile flange to increase the ultimate load capacity of the system. Youssef [7] experimentally investigated the ultimate load capacity of W-steel beams strengthened with two GFRP plates bonded to the compressive and tensile steel flanges. Accord and Earls [5] numerically investigated the enhancement of local buckling capacity and ductility of W-section cantilever steel beams with four GFRP plates bonded to the compression flange. Harries et al. [8] conducted experiments on WT steel columns strengthened with GFRP plates bonded to the web to delay local buckling. Other GFRP strengthening arrangements were investigated on members with cruciform cross-sections [9]. Aguilera and Fam [6] reported an experimental study on T-joints made of hollow steel sections strengthened with GFRP plates. Siddique and El Damatty [10] developed a finite element technique to characterize the enhancement in local buckling capacity for steel beams strengthened with GFRP plate bonded to the compression flange. The model was based on a 13-node consistent degenerated triangular sub-parametric shear-locking free shell elements. Each layer (GFRP, steel) was modelled by a shell element while the adhesive layer joining them was idealized as 2D distributed springs with zero thickness to represent the shear stiffness and a distributed transverse spring to represent its compressibility. Zaghian [11] developed a non-conforming four-node finite shell element for the buckling analysis of steel plates strengthened with GFRP plates. While the above studies focused on developing models for predicting the local buckling strength or ultimate load capacity of steel-adhesive-GFRP systems, none of them tackled their lateral torsional buckling strength.

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Buckling solutions for composite systems in general include the work of Girhammar and Pan [12] who developed a Euler-Bernoulli buckling theory for two-layer members with deformable shear connectors. Xu and Wu [13] developed a shear deformable buckling theory for two-layer members with partial interaction. Challamel and Girhammar [14] formulated a non-shear deformable theory for the lateral torsional buckling analysis of layered composite beams that captures the effect of partial interaction between the layers. Zaghian [11] developed a non-conforming four-node finite shell element for the buckling analysis of steel plates symmetrically strengthened with GFRP plates. The previous models are limited to members with rectangular sections, and thus do not incorporate warping effects which are significant in beams of wide flange cross-sections of interest in the present study. Also, most studies neglected shear deformations in their formulations. Shear deformation effects were shown to influence lateral torsional buckling predictions in short span beams with homogeneous materials [15–19].

Pham and Mohareb [20] developed a non-shear deformable theory for the static analysis of steel beams strengthened with GFRP plates and formulated a closed solution. A shear deformable theory was developed in [21] and the field equations were solved using the finite difference technique. Finite element formulations based on shear and non-shear deformable theories were developed in [22]. Pham et al. [23] developed a model that captures the effect of pre-existing stresses induced in steel beams prior to GFRP strengthening. A common theme in the studies in [20–23] is that they are limited to linear static analysis and has not tackled buckling problems. In this respect, the present study complements past work by developing a lateral torsional buckling solution. The work of static analyses in Pham and Mohareb [20,21] has shown that shear deformation effects are more important than in homogeneous beams. As such, the present study benefits from past knowledge by incorporating the effect of shear deformation due to bending and warping into the lateral torsional buckling analysis formulation sought.

Additionally, because the modulus of elasticity of adhesives is orders of magnitude lower than those of steel or GFRP, it may provide only partial interaction between both materials. As a result, throughout pre-buckling bending, a plane cross-section for the system before deformation may not remain plane after deformation [14,24]. Traditional analysis methods based on the plane section assumption (e.g., the transformed section method) are thus expected to under-predict the displacement response [25]. Hence, the present formulation incorporates the effect of partial interaction by relaxing the plane section assumption, both throughout pre-buckling and buckling. Also, global and local warping effects are included in the present formulation owing to their importance in buckling analysis of beams with open sections.

In summary, the present study develops finite element formulations for the lateral-torsional buckling analysis of beams with wide flange steel sections strengthened with a single GFRP plate adhesively bonded to one of the flanges. Distinctive features of the theory include: (1) it is based on a 1D beam solution, (2) it captures partial interaction between steel beam and GFRP plate, (3) it includes the contribution of shear strains within the adhesive layer, and (4) it includes the effect of shear deformations due to bending and warping.

2. Statement of the problem

A wide flange steel beam with a doubly symmetric cross-section is strengthened with a GFRP plate bonded to one of the flanges through a thin adhesive layer (Fig. 1). The beam is subjected to general transversely distributed load $q_y(z, y)$ acting along the curve $y_{qy}(z)$ within the web middle surface and/or a longitudinally distributed load $q_z(z, y)$ acting along $y_{qz}(z)$. The loads are increased to $\lambda q_y(z, y)$ and/or $\lambda q_z(z, y)$ at which the member is assumed to buckle in a lateral torsional mode. It is required to determine the buckling load level λ and the corresponding buckling mode by developing one-dimensional finite element formulation.

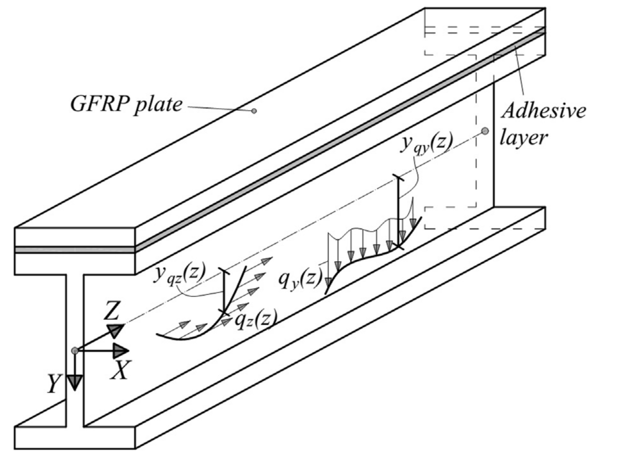

Fig. 1. A GFRP-reinforced steel beam under the application of distributed loads.

3. Assumptions

The assumptions of the present theory are an extension of those adopted under Vlasov [26] and Gjelsvik [27] beams to the composite beam, i.e.,

(i) In line with Vlasov theory, the section contours for the beam and the GFRP plate are assumed to remain un-deformed in their own plane,
(ii) The displacement fields are expressed according to the Gjelsvik beam theory [27] which captures global and local warping effects,
(iii) The steel beam and the GFRP plate are assumed to act as Timoshenko beams, i.e., their rotations about the x, y axes are considered distinct from the derivatives of the transverse and lateral displacements. The assumption is further extended to warping which is assumed to be distinct from the derivative of the angle of twist.

The following additional kinematic assumptions are also made:

(iv) Perfect bond is assumed at interfaces between the adhesive-GFRP and adhesive-steel interfaces,
(v) The adhesive is assumed to act as a flexible elastic material with a small modulus of elasticity relative to those of the beam or GFRP. As a result, the adhesive internal strain energy due to longitudinal normal stresses is considered negligible compared to that of the GFRP and steel,
(vi) The compressibility of the adhesive layer in the transverse direction is assumed negligible compared to the transverse displacements of the GFRP and the steel section, i.e., the transverse displacement of the steel beam and the GFRP can be assumed to be nearly equal,
(vii) The displacement fields within the adhesive are assumed to have a linear variation across the thickness,
(viii) Within the steel and GFRP, only the longitudinal normal stresses and the shear stresses in the tangential plane are assumed to contribute to the internal strain energy while contributions of all other stress components are assumed to be comparatively negligible.

Finally, the following assumptions are made regarding the materials and buckling configurations

(ix) The steel, GFRP and adhesive are assumed to be characterized by two material constants; the Young modulus and the shear modulus in a manner akin to linearly elastic isotropic materials. The time-dependent properties of the adhesive are omitted in the present pre-buckling analysis. If such properties are known,