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Numerical and analytical investigation of tensile behavior of non-laminated and laminated CFRP straps

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A B S T R A C T

The tensile behavior of non-laminated and laminated CFRP straps composed of up to 100 layers was numerically and analytically investigated. The failure mode in non-laminated straps changed at 20–30 layers from brittle and sudden rupture of the outermost layer to progressive rupture starting from the innermost layer, due to the different non-uniform strain distributions across the layers. Non-laminated straps showed a significantly higher load-bearing efficiency for layer numbers higher than 20 and exhibited lower sensitivity to tape anisotropy and friction at the strap/pin interface than laminated straps. An empirical model was established to estimate the ultimate load of non-laminated straps with up to 100 layers and an analytical model was derived to predict the load-bearing efficiency of laminated straps, taking into account the strap anisotropy and friction at the strap/pin interfaces.

1. Introduction

Strap anchorage methods have been developed to overcome the difficulties of anchoring fiber-reinforced polymer (FRP) tension members, in particular in the case of carbon fiber-reinforced polymers (CFRPs) since carbon fibers are strongly anisotropic, i.e. exhibit much lower mechanical properties in the transverse fiber direction than in the fiber direction [1]. Non-laminated [1,2] and laminated [3] straps are differentiated. In the former, relative displacements between the layers can occur while in the latter the layers are laminated together preventing relative displacements. Both strap types are manufactured by winding continuous CFRP tapes around two steel pins. Non-laminated CFRP straps have already been successfully used in strengthening applications for different structures such as concrete flat slabs [4], box girders [5], timber roofs [6] and masonry walls [7]. Laminated CFRP straps have been used for ground anchors [8,9] and rigging systems in sailing yachts [10].

The tensile behavior of the straps was investigated in both non-laminated [1,2,11] and laminated [1,12] cases. For the non-laminated case, tensile experiments on the CFRP straps with 10–70 layers were presented in [2]. A decrease of the load-bearing efficiency of the straps, R_u, – i.e. the ratio of the obtained ultimate load to the predicted one based on the material strength – was observed with the increasing outer to inner radius ratio, r_0/r_i, achieved by increasing the layer number or decreasing r_i. However, no detailed analysis of the reasons for this decrease was conducted. Furthermore, tensile experiments on seven-layer CFRP straps were presented in [11], where a corresponding finite element (FE) model was also developed. Based on the experimental and numerical results, the strain distributions among the layers at different locations of the straps and the failure mechanisms were investigated. However, the analysis was limited to seven-layer straps. For straps with a large layer number, e.g. 70, no detailed analytical or numerical models exist that would explain their load-bearing behavior.

For laminated straps, analytical models for high r_0/r_i values (1.8–3.0) were first developed by Conen [13] based on the thick wall cylinder theory; the models were validated by tensile experiments on glass fiber-reinforced polymer (GFRP) straps. In [1], tensile experiments on 45 CFRP straps composed of 5–15 layers were presented, based on which several analytical models including the Conen model were used for predicting R_u in relationship to different r_0/r_i values; however, the predicted results were 15–45% higher than the experimental ones. Other numerical and analytical investigations were also conducted to analyze the stress distribution in the semicircular parts of the laminated straps [12,14]; however, no analytical model for predicting the load-bearing efficiency (R_u) has been established.

In this paper, the tensile behavior of both non-laminated and laminated straps with layer numbers of up to 100, corresponding to $0 < r_0/r_i < 1.5$, which covered the r_0/r_i range of all the CFRP straps reported in the literature [1,2,4–6,8,9,15–17], was systematically investigated. For the non-laminated straps, stress and strain distributions between constituent layers, failure mechanism and reason of decreasing load-bearing efficiency with increasing radius ratio were analyzed by

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Nomenclature

The following symbols are used in this paper:

D	pin diameter
E_i	elastic modulus in i direction
E_i'	modified elastic modulus
E_v	square root of E_1'/E_2'
F	applied strap load
F_{1P}	first peak load
F_{Li}	rupture load of layer L_i
$F_{ult,th}$	theoretical capacity
F_{ult}	ultimate load
n	layer number
R_u	load-bearing efficiency
$R_{u,mod}$	modified R_u
p_i	inner pressure
r_i	inner radius of strap
r_o	outer radius of strap
t	tape thickness
w	tape width
ΔF	difference between first peak and ultimate loads
ΔR_u	difference of R_u obtained from analytical and FE models
γ_i	elastic slip
ε	strain in individual layer
ε_m	median strain
σ_R	radial stress
σ_T	tangential stress
σ_t	mean tensile strength
μ	coefficient of friction
ν_{ij}	Poisson's ratios

further developing the FE model presented in [11] where only seven-layer straps were studied. For the laminated straps, similar investigation was conducted by using both numerical and analytical methods, in which two critical factors – the orthotropic material properties and friction at the pin/CFRP interface –, which were ignored in the existing models, were taken into account and a new analytical model was subsequently derived. Finally, an explicit comparison between non-laminated and laminated straps, from both the mechanical and practical points of view, is presented.

2. FE modeling of non-laminated straps

In the previous work [11], 3D FE models developed using the commercial Finite Element Analysis (FEA) software ABAQUS 6.11 were presented for seven-layer non-laminated strap specimens; the CFRP straps were modeled using 3D shell elements. In this study, 2D FE models, where the whole thickness of the tape layer was modeled, were developed, while the material properties and the simulation method of the interface behavior were maintained the same as in the 3D models. The validation of the developed 2D modeling method was conducted on the seven-layer strap by comparing the new results with the experimental and numerical 3D results obtained in [11]. By using 2D models, the layer number of simulated straps, n, could be extended up to 70, i.e. eight FE models in total were built with n = 1, 7, 20, 30, 40, 50, 60 and 70 (designated as N1–N70). Detailed analyses including failure mechanism, strain distribution among the layers and load-bearing efficiency were carried out based on the validated model.

2.1. Description of 2D FE model

2.1.1. Model geometry

To avoid convergence difficulties caused by the large contact surfaces and element numbers if using 3D models for the straps with a large layer number, the models were simplified into 2D ones, as shown in Fig. 1. The input material properties and model dimensions remained the same as in the 3D model [11], except the layer number, i.e. the pin-to-pin distance was 370 mm, the width, w, and thickness, t, of the tape layer were 30 and 0.135 mm respectively and the inner diameter of the strap, identical to the pin diameter, was 55 mm (see Fig. 1). Furthermore, the anchoring of the innermost layer by friction and the

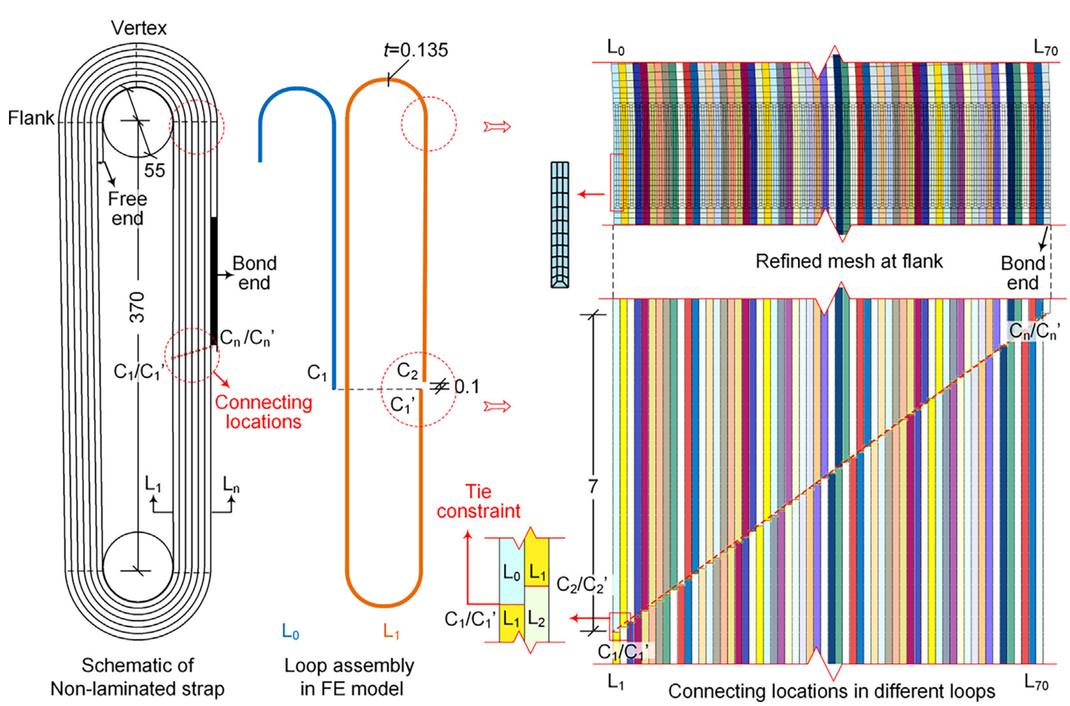

Fig. 1. FE model of non-laminated straps (dimensions in [mm]).