Strengthening effects of CFRP layers for thin-walled structures under various loading conditions

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Abstract

Title	Strengthening effects of CFRP layers for thin-walled structures under various loading conditions

Thin-walled structures including large thin-walled steel cylinders (TSCs) or thin-walled steel storage tanks (CSSTs) have extremely important roles in the development of economy and infrastructures. Many of them were constructed long time ago and suffered degradation because of ageing or corrosion. Therefore, the strengthening of the thin-walled structures against buckling and improving the ultimate strength of the tanks was necessary for the sustainable development of economy and infrastructures. In this thesis, strengthening effects of CFRP layers for thin-walled structures under various loading conditions will be investigated by theory, experiments, and finite element analysis (FEA). The applied loads include axial compression, shear load, seismic load, and bending shear load. The contents of the thesis divide into several chapters. Chapter 1 introduces the buckling problems of thin-walled structures and research objectives. Chapter 2 presents the mechanical properties of the lamina, laminate, and general relationships for laminated composite materials.

In chapter 3, the effects of CFRP layers on TSCs under compressive load were surveyed by both experiments and finite element analysis. Some important points were highlighted in this chapter. Firstly, circumferential CFRP layers have important roles for keeping the stability of TSCs after reaching the maximum loading. The loads decrease slowly and are more stable in CFRP-strengthened models after reaching the maximum loads. Circumferential CFRP layers can constrain the out-of-plane deformation of TSCs effectively, reduce the circumferential strain of TSCs, and increase the load-carrying capacity of thin-walled structures. Secondly, there were some different strengthening effects of different types of CFRP layers depending on the angles of fibers. The appearance of circumferential CFRP layers will bring higher strengthening effects for buckling restraint of TSCs under axial compression. Only 90 degrees of CFRP layers should not be used to strengthen the TSCs under axial compression. Thirdly, FEA can be used effectively to investigate the behaviors of TSCs under compressive load because good correspondences were found between experimental and FEA results. Finally, a theory of CFRP-strengthened steel lamination in the linear and elastic area is proposed to calculate exactly the characteristics of strengthened TSCs under compressive loads. This theory can be used to determine the stress-strain relations and von Mises stress of strengthened TSCs in linear and elastic areas.

Chapter 4 analyzed the effects of CFRP layers on the shear strength of thin steel plates by theory, experiments and finite element analysis. Some following main points were obtained from this chapter. Firstly, angle-CFRP was proven to increase the critical and ultimate shear strength of thin steel plates. The strengthening effects of 45 degrees-CFRP layers are a little bit higher than 0/90 degrees-CFRP layers. Secondly, there were good agreements found between experiments, theory and finite element analysis.

Therefore, the proposed equations can be used to predict the critical and ultimate shear load for strengthened-thin steel plates with high accuracy.

In chapter 5, a new experimental method using steel balls to create the internal pressures for thin-walled structures was presented. In addition, the theory of CFRP-strengthened aluminum section was provided to determine the mechanical characteristics of the section. There were good correspondences between theory and experimental results; therefore, steel balls can be effectively used to investigate the behaviors of thin-walled structures and CFRP-strengthened thin-walled structures under seismic loads.

In chapter 6, FEA was used to survey the load-carrying capacity and buckling modes of cylindrical steel storage tanks under bending shear load with and without CFRP strengthening. The effects of the angle of fibers and the strengthening heights are investigated throughout the analysis. Based on the analysis and calculated results, some following main points may be highlighted in this chapter. Firstly, the main buckling failure of tanks without CFRP strengthening was elephant foot bulge. Then, the elephant foot bulge at the bottom of the tanks was limited and the shear buckling occurred at the tank's walls when strengthening with CFRP layer. Also, the impact of internal pressure on the tanks was decreased when CSSTs were strengthened by CFRP layers. Secondly, the ultimate strength of the tanks was increased when strengthening the tanks with CFRP layers and the increased level of ultimate strength was corresponding with the increase of the numbers of CFRP - strengthened layers. Moreover, the strengthening effects of CFRP layers were higher when the CSSTs subjected to higher values of internal pressures. In addition, when CSSTs subjected to low internal pressure or strengthened with fewer CFRP layers, the strengthening effects are nearly the same with 20% and 50% strengthening heights. Therefore, it is better to choose 20% strengthening heights because of economic effects. Finally, circumferential CFRP layers have better effects for tanks under bending shear loads because of the main failure modes of tanks are elephant foot bulge. It is recommended that only angled fiber of CFRP layers should not be used to strengthen when the tanks subjected to high values of internal pressures and bending shear loads.

Publication lists

[1]. Phan Viet Nhut and Yukihiro Matsumoto. Fundamental Study about the Impacts of Fiber's Angle for the Strengthening of Steel Storage Tanks under Bending Shear Load. International Journal of Civil Engineering and Technology (IJCIET). Volume 9, Issue 4, April 2018, pp. 1509–1515.

[2]. P V Nhut and Y Matsumoto. The Effects of Carbon Fiber Reinforced Polymer Strengthening on Cylindrical Steel Storage Tanks under Bending Shear Load. IOP Publishing: IOP Conf. Series: Materials Science and Engineering 371 (2018) (2018 3rd International Conference on Building Materials and Construction, 23–25 February 2018, Nha Trang, Vietnam). Doi:10.1088/1757-899X/371/1/012025

[3]. Phan Viet Nhut and Yukihiro Matsumoto**.** The effects of the angle of carbon fiber for the strengthening of steel storage tanks under bending shear load. Proceeding of the 20th International Summer Symposium, Japan Society of Civil Engineers, August 2018, pages 1-2.

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Notation

The symbols used in this thesis are listed below. Only one meaning has been assigned to each symbol unless otherwise defined in the text where the symbol occurs.

Symbol	**Meaning**
υ_f	Volume fraction of fiber in laminae
υ_m	Volume fraction of matrix in laminae
w_f	Weight (mass) fraction of fiber in laminae
w_m	Weight (mass) fraction of matrix in laminae
V_f	Volume of fiber in laminae
V_m	Volume of matrix in laminae
W_f	Weight (mass) of fiber in laminae
W_m	Weight (mass) of matrix in laminae
ρ_f	Weight density (mass density) of fiber
ρ_m	Weight density (mass density) of matrix
ρ_c	Weight density (mass density) of FRP composite laminae
t_f	Thickness of fiber in laminae
t_m	Thickness of matrix in laminae
t_c	Thickness of FRP composite laminae
E_x	Longitudinal modulus in the fiber direction (x direction)
E_y	Transverse modulus perpendicular to the fiber direction (y direction)
G_{xy}	In-plane shear modulus
E'_x	Longitudinal modulus of laminate in the fiber direction (x direction)
E'_y	Transverse modulus of laminate perpendicular to the fiber direction (y direction)
G'_{xy}	In-plane shear modulus of laminate
ν_f	Fiber volume fraction
ν_m	Matrix volume fraction
ν_{xy}	Major Poisson ratio
t_s	Thickness of steel
E_s	Elastic modulus of steel
r	Inside radius of thin-walled steel cylinder

t_k	Thickness of lamina k
h	Thickness of laminate
θ	The angle between the local and global axes
E	Elastic modulus of isotropic material
μ	Poisson' s ratio of isotropic material
k_s	Shear buckling stress parameter
b	Height of rectangular plate
a	Width of rectangular plate
t	Thickness of rectangular plate
τ_{cr}	Critical shear stress of rectangular plate
D	Flexural rigidity of rectangular plate
V_u	Ultimate shear load of rectangular plate
V_p	Plastic shear force of rectangular plate
τ_y	The yield shear stress of rectangular plate
σ_y	The yield stress of rectangular plate
α	Aspect ratio of rectangular plate
D_1, D_2, D_3	Stiffness coefficients of orthotropic materials
E_1	Elastic modulus of orthotropic material in x direction
E_2	Elastic modulus of orthotropic material in y direction
G_{12}	In-plane shear modulus
v_{ij}	Poisson's ratio of orthotropic material
$D_1^{'}, D_2^{'}$	Stiffness coefficients of CFRP-strengthened steel plate
$E_1^{'}$	Elastic modulus of CFRP-strengthened steel plate in x direction
$E_2^{'}$	Elastic modulus of CFRP-strengthened steel plate in y direction
$v_{ij}^{'}$	Poisson's ratio of CFRP-strengthened steel plate
E_L	Young's modulus of main direction of CFRP
E_{eq} :	Equivalent elastic modulus of CFRP layer in the shear direction
t_c :	Total thickness of CFRP layers
t :	Thickness of thin-walled steel plate
E_s :	Elastic modulus of thin-walled steel plate

p_s:	Static pressure
ρ:	Density of steel
υ_s:	Volume fraction of steel balls
h_l:	Depth of steel ball
g:	The acceleration due to gravity
d:	Diameter of cylinder
σ_h:	Hoop stress (circumferential stress in cylinder)
t_{cy}:	Thickness of the cylinder
t_a:	Thickness of aluminum plates
p_i:	Impulsive pressure
p_{ci}:	Convective pressure
$A_i(t)$:	Pseudo-acceleration for impulsive mode
$A_{cn}(t)$:	Pseudo-acceleration for convective mode
T_{imp}:	Natural period for impulsive mode
T_{con}:	Natural period for convective mode
x(t):	Instantaneous deformation of the system
ξ:	Damping factor
$\sigma_{h,eq}$:	Equivalent tensile hoop stress
p:	Internal pressure