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Behaviour of Glass FRP Composite Tubes Under Repeated Impact for Piling Application

By

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A dissertation submitted for the award of

DOCTOR OF PHILOSOPHY

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Abstract

Fibre composites have been a viable option in replacing traditional pile materials such as concrete, steel and timber in harsh environmental conditions. On the other hand, the emergence of fibre reinforced polymer (FRP) composite tubes as a structural component and their corrosion-resistant characteristics made these materials potential in piling application. Driving these piles, however, requires more careful consideration due to their relatively low stiffness and thin walls. The possibility of damaging the fibre composite materials during the process of impact driving is always a concern. Research has therefore focused in understanding the impact behaviour of these materials in order for them to be safely and effectively driven into the ground.

This study investigated the behaviour of composite tubes subjected by repeated axial impact. The effects of impact event (incident energy and number of impact) on the instantaneous response and the residual properties of composite tubes were examined. Tubes made of glass/vinyl ester, glass/polyester, and glass/epoxy materials of different cross sections were considered. The impact behaviour of the tubes was experimentally and analytically investigated.

An experimental study on the repeated impact behaviour of square composite tube was conducted. The result showed that the dominant failure mode of the tube repeatedly impacted was characterised by progressive crushing at the upper end. This failure was manifested by inter and intra laminar cracking and glass fibre ruptures with simultaneous development of axial splits along its corners. It was found that the drop mass and impact velocity (or drop height) have pronounced effects on the collapse of the tubes at lower incident energies. Their effects, however, gradually decrease at relatively higher energies. The result also indicated that the incident energy is the major damage factor in the failure of tubes for lower number of impacts. On the contrary, the number of impacts becomes the key reason as soon as the value of incident energy decreases.

The effects of the damage factors such as the level of impact energy, the impact repetitions, and the mass impactor on the residual (post-impact) properties were also examined. The result of the investigation revealed that these factors significantly influenced the residual strength degradation of the impacted tubes. In contrast, the residual modulus was found to be less affected by these factors since the damage brought by them is localised in most of the cases. The maximum reduction on the residual moduli is roughly 5%. On the other hand, the residual strengths degraded by up to 10%. The flexural strength of the tube was the most severely affected by the impact damage than its compressive and tensile strengths. This result was due to the fact that the impact damage on matrix and fibre both contributed on the flexural strength degradation. Moreover, the presence of matrix cracks or delamination lead to an increase in buckling instability during the flexural test, resulting to a much higher degradation compared to the other strengths. The comparison of the residual compressive strengths sourced at different locations along the height of the tube revealed that the strength reduction varied with its location. The degradation of the compressive strength of the impacted tube decreased when its location from the top of the tube increased. This result indicated that the influence of impact damage on the degradation of residual compressive strength of the tube is concentrated only in region closer to the impact point.

Finally, theoretical prediction using the basic energy principle was performed to gain additional understanding on the damage evolution behaviour of composite tubes subjected by repeated axial impact. The damage evolution model was verified through experimental investigation on a 100 mm square pultruded tube. The model was applied to composite tubes of different cross sections and materials made from vinyl ester/polyester/epoxy matrix reinforced with glass fibres. It was found that the experimental results on a 100 mm square pultruded tube and the proposed damage model agreed well with each other. The variation is less than 10% indicating that the model predicted reasonably the damage evolution of the tube subjected by repeated impact loading. It was also found that the energies describing the low cycle, high cycle, and endurance fatigue regions of the composite tubes are largely dependent on their corresponding critical energy E_c. The higher the E_c values, the higher the range of energies characterising these regions. The repeated impact curves (or E_c) of tubes made from glass/epoxy is higher compared to the other matrix materials. Similarly, circular tubes have greater E_c values of comparable square and rectangular tubes.

From this study, an improved understanding of the behaviour of glass fibre FRP composite tubes under repeated axial impact can be achieved. The information provided in this study will help in developing efficient techniques and guidelines in driving composites piles.

Certification of Dissertation

I certify that the ideas, experimental work, results, analysis and conclusions reported in this dissertation are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any award, except where otherwise acknowledged.

-- / /

Signature of Candidate

Endorsed:

-- / /

Signature of Supervisor/s

-- / /

Signature of Supervisor/s

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Notations

Roman alphabets

Notation	***Description***
A	Cross-sectional area of tube/coupon specimen
a	distance between one of the end supports and the nearest applied load, parametric constant, acceleration
a_t	Acceleration as a function of time or at present time increment
$a_{t\text{-}1}$	Acceleration at previous time increment
b	Width of the tube/coupon specimen or parametric constant
c	Neutral axis depth of the tube or parametric constant
c_w	Compression wave velocity
D	Damage parameter
d	Depth of the tube
E	Modulus of elasticity
E_{abs}	Absorbed energy
E_c	Critical energy (energy causing the failure of tube at one impact)
E_{comp}	Compressive elastic modulus of tube/coupon specimen
$(E_c)_{Dynamic}$	Critical energy obtained from dynamic (impact) test
E_f	Flexural elastic modulus
E_{im}	Impact energy
E_{in}	Incident energy
E_K	Kinetic energy
E_P	Potential energy
$(E_c)_{Quasi\text{-}static}$	Critical energy obtained from quasi-static compressive test
E_{sat}	Saturation energy
E_t	Tensile elastic modulus
E_T	Total energy
E_{ws}	Energy as a function of displacement
E_{wt}	Energy as a function of time
F_s	Load at present displacement increment
F_{s-1}	Load at previous displacement increment
F_t	Impact load as a function of time
g	Acceleration due to gravity
h	Drop height
h_0	Drop height (used in Appendix C)
j	Inner depth of the tube
k	Inner width of the tube
l	Length of the tube /coupon specimen
l_s	Test span in flexure
L	Length of the tube (used in Appendix C)
M_g	Fibre glass content in mass percentage
m	Mass of the impactor
m_c	Critical impact mass

m_0	Initial mass of the specimen used in fibre fraction test
m_1	Initial mass of the dry crucible used in fibre fraction test
m_2	Initial mass of the dry crucible plus dried specimen used in fibre fraction test
m_3	Final mass of the crucible plus residue used in fibre fraction test
m_m	Equivalent mass at the m^{th} point (used in Appendix C)
N	Number of impact
N_f	Number of impacts to initiate failure/collapse of the tube
N_{max}	Maximum number of impact
P_{pc}	Peak compressive load of tube/coupon specimen
P_{pf}	Peak flexural load of tube/coupon specimen
P_{pt}	Peak tensile load
$(P_m)^0$	Maximum load at the 1st impact
$(P_m)^N$	Maximum load at the N^{th} impact
I	Moment of inertia
I_x	Moment of inertia along the x-axis
I_y	Moment of inertia along the y-axis
t	Thickness of the coupon specimen
$R(N_f)$	Reliability of N_f
r_i	Internal radius of the chamfered corner of the rectangular tube
r_e	External radius of the chamfered corner of the rectangular tube
s_m	Travelled distance by the wave at the m^{th} point (used in Appendix C)
s_t	Displacement as a function of time
t	Present time increment
$t–1$	Previous time increment
v	Impact velocity
v_{ff}	Volume of the specimen used in fibre fraction test
v_m	Wave velocity at the m^{th} point (used in Appendix C)
v_0	Initial velocity of the impactor before hitting the target
v_t	Velocity as a function of time or at present time increment
v_{t-1}	Velocity at previous time increment
z	Pile impedance

Greek letters

Notation	***Description***
α	Ratio of the loading rates between quasi-static compressive and impact tests
β	Correlation factor
ε_{pc}	Peak compressive strain of tube or coupon specimen
ρ	Mass density/specific mass
ρ_t	Mass density of the tube (used in Appendix C)
σ_{pc}	Peak compressive stress of tube or coupon specimen
σ_{pf}	Peak compressive stress
σ_{pt}	Peak tensile stress
σ_1	stress measured at the strain values $\varepsilon_1 = 0.0005$
σ_2	stress measured at the strain values $\varepsilon_2 = 0.0025$
θ	Life duration