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Dynamic inversion characteristics of composite reinforced tubes

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ABSTRACT

An analytical solution is presented to study the energy absorption properties of composite reinforced tubes undergoing freely dynamic external inversion. A finite element method is used to indirectly validate the analytical solution for dynamic inversion characteristics of composite reinforced tubes. Compared with finite element results, the feasibility of the analytical method is simply verified. The effects of composite layer (viz. fiber layer thickness and fiber reinforced orientation), dynamic loading and section shape of tube on the inversion characteristics of composite reinforced tubes are described and investigated in examples, respectively.

1. Introduction

In recent years, people are increasingly concerned about the safety performance of vehicles, thus various energy-absorbing structures are widely used to improve their crashworthiness, where deformation of circular metal tubes under compressive axial force is a conventional energy absorption mechanism (Lu and Yu, 2000; Eyvazian et al., 2014, 2016). Among various deformation modes, inversion of circular metal tubes is preferred as a stable and controllable mechanism, with steady load-displacement curves, which can be applied to design collapsible steering column or other energy absorbing devices (Yu et al., 2015, 2016; Qiu et al., 2013, 2014). It's notable that two parameters are used to describe inversion performance of tubes: knuckle radius and inversion load, but the inversion load is more important of the two on account of manifesting energy absorption capacity of tubes undergoing free external inversion. Over the same descending displacement, greater inversion load leads to more work i.e. absorbing more energy.

Dating back to the 1960s, Kroell. (1962) first introduced the mechanism of metal tubes' inversion when designing axial crashworthy structures for vehicle use. Four modes of tubes' inversion were described and relative experimental data were given, namely free external inversion, free internal inversion, external inversion with a die and internal inversion with a die.

Employing the energy conservation principle and the inversion load minimization assumption, Guist (Guist and Marble, 1966) established a simplified model to derive an analytical solution with the aim to predict the inversion load and knuckle radius of metal tubes. It was turned out that the prediction of the inversion load was reported 20%–30% less than the test data while the prediction of the knuckle radius nearly twice the counterparts in the experiments.

To narrow the gap between experimental data and analytical predictions of the knuckle radius, Reddy (1992) restudied this problem in 1992, adopting the rigid, linear strain-hardening material model, Tresca yield criterion and associated flow rules. A new analytical solution was produced and some specific parameters could provide rather accurate predictions of the knuckle radius.

Compared with the conventional 2D models, Qiu (Qiu et al., 2013, 2014) put forward a three-dimensional model for quasi-static free external inversion of circular metal tubes, providing a better prediction on the inversion load. Colokoglu and Reddy (1996) examined the effects of strain rate and inertia during dynamic inversion process of circular metal tubes.

So far, composite materials have been gaining momentum, widely used in the aerospace industry. In addition to high specific strength and stiffness, their excellent energy absorption performance attracts much attention. Compared with conventional metallic materials, composite materials possess a higher specific energy absorption capacity (i.e. energy absorbed by per unit mass), thus more capable in terms of actual energy absorbing performance

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Nomenclature

P	Inversion load
P_y	Yield load of metal tube under axial compression
r	Knuckle radius i.e. radius of the semicircular deformation zone
R	Radius of circular tube
a, b	Cross section parameters of elliptical-section tubes
g, G	Geometric parameters of composite-section tubes
d	Distance between the symmetric axis Z and any point of inversion zone in the cross section of any shape
θ	Angle subtended at center over the meridian length from *B1* to *B2*
θ_0	Ultimate value of angle θ when the maximum circumferential strain equals to the ultimate tensile strain of composite layer
C_{B1}, C_{B2}, C_{B3}	Perimeter of section at point $B1$, $B2$ and $B3$, respectively
h_m	Thickness of metal layer
h_c	Thickness of composite layer
h	Total thickness of fiber reinforced metal tubes
ρ_m	Density of metal material
ρ_c	Density of composite material
ρ	Effective density of composite reinforced tubes
V_m and V_c	Volume percentages of metal and composite material in composite reinforced tubes, respectively
V	Total volume of tubes
m	Mass of tubes
V_P	Loading velocity
V_0	Relative velocity of tubes entering the inversion deformation zone
V_{B1}	Descending velocity at the point $B1$ of inversion deformation zone
δ	Descending distance of the free end of tubes
δ_{B1} ,δ_{B2}, δ_{B3}	Flow length of tube at points $B1$, $B2$ and $B3$, respectively
δ_{B1B2}	Average downward displacement of the inversion zone between $B1$ and $B2$
ε_{mc}	Strain of metal layer along the circumferential direction of tubes
ε_{mz}	Strain of metal layer along the axial direction (the symmetric axis$Z$) of tubes
ε_{mt}	Strain of metal layer along the radial direction of tubes
ε_{eff}	Equivalent strain of metal material
W_P	External work done by the dynamic axial load
W_V	Kinetic energy of tubes as covering a distance δ at velocity V_P
W_I	Work done by radial inertia force in the inversion deformation zone
W_S	Energy dissipated due to circumferential stretching
W_B	Energy dissipated due to bending deformation at $B1$ and $B2$
Y_0	Initial yield stress of metal material
$\overline{Y_0}$	Dynamic yield stress of metal material
Y_c	Compressive yield stress of composite material
E	Young's modulus of metal material
E_P	Strain-hardening modulus of metal material
D, q	Parameters describing dynamic behavior of metal material
M_0	Static ultimate bending moment at the point $B1$
M_{0d}	Dynamic ultimate bending moment at the point $B1$
M_1	Ultimate bending moment of bi-material tubes acquired by calculation
M_2	Plastic ultimate bending moment of metal tubes
x	Distance between the neutral axis and the inner wall in the cross section
y	Distance between any point and the inner wall in the cross section
ω	Angular velocity of any element in the inversion deformation zone
γ	Angular acceleration of any element in the inversion deformation zone
F_r	Radial inertial force of any element in the zone between $B1$ and $B2$
F_{rz}	Axial component along Z axis of the radial inertial force
ε_s	Maximum circumferential stretching strain of metal layer
t_s	Time to reach the maximum circumferential strain ε_s
$\dot{\varepsilon}$	Uniaxial plastic strain rate of metal layer
κ	Curvature of the neutral axis
t_h	Time to reach the variation of curvature taking place over a length $5h$
$\dot{\kappa}$	Change rate of the neutral axis curvature
α	Ply orientation angle of fiber layer
A	Mass correction coefficient
σ_L and ε_L	Ultimate stress and strain along the reinforced material's main directions L (parallel to fibers) respectively
σ_T and ε_T	Ultimate stress and strain along the reinforced material's main directions T (perpendicular to fibers) respectively
τ_{LT} and γ_{LT}	Ultimate shear stress and strain in $L-T$ plane respectively
E_{cct} and E_{ccc}	Tension and compression modulus of composite layer along the circumferential direction of tubes, respectively
E_{czt} and E_{czc}	Tension and compression modulus of composite layer along the axial direction of tubes, respectively
σ_{cc} and ε_{cc}	Ultimate stress and strain of composite layer along the circumferential direction of tubes respectively
σ_{cz} and ε_{cz}	Ultimate stress and strain of composite layer along the axial direction of tubes respectively
σ_{cct} and ε_{cct}	Ultimate tensile stress and strain of composite layer along the circumferential direction of tubes respectively
σ_{ccc} and ε_{ccc}	Ultimate compressive stress and strain of composite layer along the circumferential direction of tubes respectively
σ_{czt} and ε_{czt}	Ultimate tensile stress and strain of composite layer along the axial direction of tubes respectively
σ_{czc} and ε_{czc}	Ultimate compressive stress and strain of composite layer along the axial direction of tubes respectively