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Axial crushing of pressurized cylindrical tubes

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ABSTRACT

The crushing response of the pressurized cylindrical tubes under low-speed axial crushing is investigated by both numerical simulations and theoretical analysis. The internal pressure inside the tubes varies in a wide range from 0% to 80% of the tube's yield pressure. Numerical simulations with lower internal pressure are verified by the experiments reported in literatures. It is shown that under axial crushing the tubes with lower internal pressure deform into the mixture of symmetric mode and unsymmetrical mode. With the increase of internal pressure, the tube's deformation under axial crushing is dominated by the symmetric mode. The total load-carrying capacity of the pressurized structure increases with the internal pressure. However, the load-carrying capacity of the tube wall itself decreases with the increase of internal pressure once the pressure is greater than 13% of the yield pressure. This behavior is very different from the foam-filled tubes, for which the load-carrying capacity of the tube wall is enhanced by the filler inside. Based on the symmetric fold's evolution process observed from numerical simulations, an analytical model is proposed to establish the expression of the tube wall's load-carrying capacity in relation to the internal pressure and the tube's size. It is shown that the tube wall's load-carrying capacity under higher internal pressure decreases with the internal pressure, while it increases with the cross-sectional area of the tube. By combining the analytical predictions obtained in the present paper under symmetric mode and that under non-symmetric mode reported in literature, the critical internal pressure for the transformation between the two deformation modes is estimated. All the analytical predictions are found to be in good agreements with the numerical simulation results.

1. Introduction

As a classical kind of energy absorption components, tubes have been widely adopted in aircraft and vehicle structures. During the accidental impacts, they are crushed axially to absorb energy effectively while limiting the crushing force [1]. When the cylindrical tubes were axially compressed, four kinds of deformation modes are observed: ring mode (symmetric mode), diamond mode (non-symmetric mode), mixed mode and Euler buckling, as dictated by the tube's length and the ratio of the tube's diameter to its wall-thickness [2–4]. Alexander [5] first established an analytical model to predict the average crushing force of cylindrical tubes deforming with the ring mode. Then his work was modified in later references [6,7] to improve the accuracy. Bardi et al. [8] compared numerical crushing responses with those of the major plastic hinge models for the axisymmetric crushing mode. For the tubes deforming with diamond mode, the proposed analytical models are not as successful as the ring mode due to the complex deformation process of the tube wall. Most of such models on the diamond mode involve the bending of the triangle elements around the plastic hinge lines. However, it is difficult to theoretically determine the number of the elements, which needs to be known in advance [9]. Thus, empirical formulas based on experiments are usually employed in predicting the tubes' average crush force [2].

Cellular materials have been proved to possess effective energy absorption capability [10–12], thus some researchers focused on the tubes filled with cellular materials inside. It is shown that the foam filler beneficially contributes in terms of failure modes, resulting in a much more stable crushing manner during axial compression tests [13]. Toksoy and Guden [14] carried out a series of experiments and found that the foam filling reduced the fold length and changed the deformation mode of the tube from multi-lobe mode to axisymmetric mode. Similar phenomena were observed in the wood-filled tubes [15]. Besides, Duarte [16] experimentally found that a good interface bonding between the tube and the filled foam contributed to a more axisymmetric deformation without distortion, while a lack of interface bonding resulted in an irregular fold with a certain distortion.

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Nomenclature

E	energy dissipated by tube wall
E^b_{DE},E^s_{DE}	plastic bending energy and stretching energy, respectively, of arc DE
$\overline{E^b}$,$\overline{E^s}$	plastic bending energy and stretching energy, respectively, absorbed by the representative fold per unit displacement
F_{tw}	crushing force suffered by tube wall
F_p	force to balance internal pressure, $F_P=\pi R^2 p$
F_{total}	total compression force imposed by crushing plate F_{total}=F_{tw}+F_p
H_0, H_f	initial and final length of representative fold segment, respectively.
L	length of wall section
Mo	fully plastic bending moment per unit length of tube wall, $M_0=\frac{Yt^2}{4}$
p_Y	yield pressure of tube
R	radium of tube
$Rcenter$	distance from centroid of area BDEF to tube's axis
r	radius of arc AB, see Fig. 8
t	thickness of tube wall
ΔV	lateral change in internal volume surrounded by fold segment during its evolution process
W_F	work done by crushing force
W_p	work done by internal pressure
Y	yield stress of tube wall material
α, β, γ, δ, ζ, θ, λ, φ	angle of each section, as shown in Fig. 8

Moreover, the mean crushing load and subsequently the specific energy absorption of the tubes were found to be enhanced by the filler [14,15]. The total crush force of the foam-filled tube can be divided into three parts, i.e., (1) the average crush force of non-filled tubes, (2) the uniaxial resistance of foam filler, and finally (3) an interaction effect [17]. Thus, the load-carrying capacity of the foam-filled tube is higher than the sum of that of the tube and the foam alone due to the interaction effect between the tube's inner wall and the foam filler [13,18].

The pulse buckling of water-filled cylindrical tubes under axial impact was experimentally and numerically investigated by Lu et al. [19], in which the water was sealed within the tube. Thus, quite high internal hydrodynamic pressure occurred inside the tube during the impact process, and the pressure rapidly increased with the crushing displacement. Under the combined action of high internal pressure and axial compression, the thin-walled tubes buckle plastically with regular and axisymmetric wrinkles. Another similar study by Paquette and Kyriakides [20] was conducted on the stainless-steel cylindrical tubes with pressured fluid inside, in which the internal pressure was controlled as fixed values during the compression process. The experimental results showed that the internal pressure lowered the axial stress–strain response of the tubes. Besides, it was observed that all the pressurized cylinders developed axisymmetric wrinkling in contrast to the non-axisymmetric buckling modes for the tubes without internal pressure. It is noticed that all their experiments were only within small deflections (axial displacement $<5\%$). If the tubes are used for energy absorption devices, their behaviors under large plastic deformations need to be investigated.

Zhang and Yu [21] explored the possible use of air-pressurized thin-walled cylindrical tubes as adaptive energy absorbers and experimentally investigated those tubes' energy absorption behaviors under axial crushing with constant internal pressure. It was shown that with the increase of internal pressure the deformation mode of the tube changed from diamond mode with sharp corners to that with round corners, and finally to ring mode. In diamond mode, the tubes' mean force increased with internal pressure on account of two mechanisms: the direct effect of the internal pressure and the interaction between pressurized air and tube wall. The second mechanism became weaker after the deformation switched to ring mode. However, no reduced load-carrying capacity of the tubes caused by internal pressure was observed in their experiments, which was different from the reports of Paquette and Kyriakides [20]. It is noticed that the internal pressure in their studies [21] was limited in the range from 0% to 30% of the tube's yield pressure, and the tubes experienced large plastic deformation. On the other hand, the tubes' axial compression reported by Paquette and Kyriakides [20] was small although the internal pressure increased up to 75% of the tube's yield pressure. Thus, more work need to be done in a wide range of internal pressure to clarify the effect of internal pressure on the force–displacement response of tubes axially crushed with large plastic deformation.

In the present paper, the crushing response of the pressurized thin-walled cylindrical tubes under axial impact was numerically investigated with the internal pressure varying in a wide range from 0% to 80% of the tube's yield pressure. Numerical simulations with lower internal pressure are verified by the experiments reported by Zhang and Yu [21]. Moreover, an analytical model is proposed to establish the dependence of the tube's load-carrying capacity on the internal pressure and the tube's own parameters.

2. Numerical simulations

2.1. Numerical model

Numerical simulations are carried out by employing the software ANSYS/LS-DYNA. A cylindrical tube without upper and bottom surfaces is put on a fixed rigid plate, and is axially crushed by another rigid plate from the top with a constant velocity $V=1$ m/s or $V=10$ m/s, as shown in Fig. 1. A constant air-pressure p is applied on the inner surface of the tube, which is always perpendicular to the tube's inner surface with a fixed magnitude during the whole crushing process. The internal pressure p is within the range from

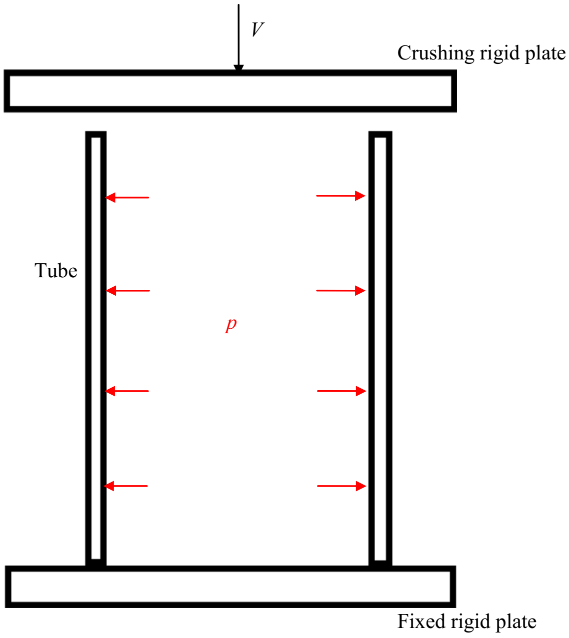

Fig. 1. Numerical model in simulations.