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Crushing behavior and energy absorption performance of a bio-inspired metallic structure: Experimental and numerical study

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ABSTRACT

A thin-walled structure inspired from a biologic creature known as balanus was investigated experimentally and numerically under quasi-static and dynamic loads for load-carrying and energy absorption properties. The structure was composed of an inner conical core with a hemispherical cap and an outer shell in frusto-conical shape and formed by deep drawing. The applied deep drawing process was modelled using nonlinear finite element code LS-DYNA to determine the residual stress/strain and the non-linear thickness distribution after the forming process. It was also shown that the load carried by the balanus structure was greater than the arithmetic sum of the load carried by the inner core and by the outer shell separately. Although the mean force increase due to interaction effect at quasi-static strain rate was approximately 5%, while it increased to roughly 26% at dynamic strain rates in drop weight experiments. The numerical models also showed that the outer shell absorbed more energy than the inner core while the difference between the energy absorbing performance of the core and shell decreased with increasing deformation rate. The effect of strain rate and inertia on the increase in crush load increased with increasing impact velocity, while the strain rate effect had greater influence than the inertia on the crush load. The increased load carrying capacity of the balanus at quasi-static and dynamic strain rates was ascribed to the interaction between the core and shell and the confinement effect of the outer shell particularly at dynamic strain rate.

1. Introduction

One of the earliest studies on the axial crushing of thin-walled cylindrical tubes dates back to 1960s [1]. A relationship between the crush force and shell thickness of metallic thin-walled tubes was derived. A self-consistent theory of the progressive folding of thin-walled rectangular columns showed that two-thirds of the plastic energy was dissipated through in-extensional deformations at stationary and moving plastic hinge lines [2]. Experimental studies performed on the tapered thin-walled rectangular cross-section metallic tubes [3,4] showed that the initial peak load decreased with increasing taper sides and the crush force efficiency increased with increasing the number of oblique sides. It was also found that the energy absorption response of tapered tubes could be controlled via their wall thickness and taper angle [5]. The crushing behavior of conical structures were also investigated [6–9]. Results have shown that thin-walled conical frusta deform under axial loading in three different modes: inversion, concertina and diamond. The most substantial variables on the energy absorbing performance were the angle and thickness rather than the bottom diameter and length of the structure [9]. In a combined geometry of a conical portion and a hemispherical cap, the hemispherical cap initially deformed by flattening followed by inward dimpling, while the conical part deformed by progressive axisymmetric folding [10]. The energy absorption of hemispherical cap was found higher under dynamic loading than quasi-static loading, attributed to the strain rate sensitivity of cap material and inertial effects [11].

When thin-walled single metallic tubes are filled with a light-weight foam, an interaction effect exists between tube wall and foam filler [12–17]. Mainly due to this interaction, the crushing forces of foam-filled tubes are higher than the sum of the crushing forces of foam (alone) and tube (alone). The encroachment of the metal tube wall into foam filler was proposed to be resulting in an additional compression in the foam filler, retarding the sectional collapse of the column [14]. The foam filling was also shown to increase the number of folds formed and decrease the fold lengths in the metallic tubes [18]. Further, the tendency for the concertina mode of deformation increased with foam filling due to the thickening effect of foam filling. Recent studies have been also on the single, double, multi-wall and multi-cell tubes [19,20].

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(a)

(b)

Fig. 1. (a) Balanus [35] and (b) bio-inspired geometry.

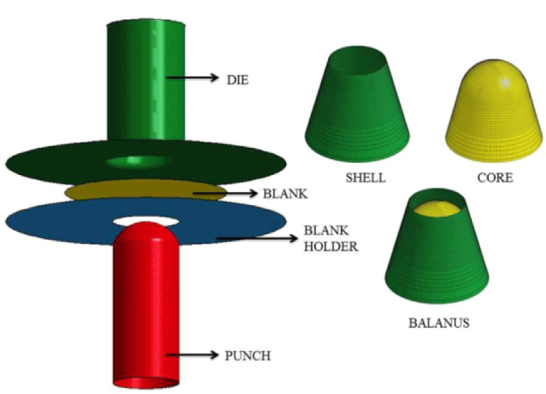
It has been noted that the similar interaction effect existed between the outer and inner tubes of bitubular structures [21] and concentric expanded metal tubes under quasi-static axial compression [22,23].

The geometry of balanus, a sea creature found on coastlines along the oceans, is composed of a conical inner core and an outer shell (Fig. 1(a)), resembling bitubular tubes. The balanus exist in extreme conditions such as on the rocks and man-made structures from mid-shore to the neritic zone and also forms part of the fouling community on the hulls of ships. The geometry of the balanus should therefore be optimized to the externally applied natural forces. As with the other bio-inspired structures such as honeycombs [24], turtle shells [25], beetle forewings [26] and peacock mantis shrimps [27], the geometry of the balanus is interesting for the development of crashworthy structures as it accommodates all three parts together: bitubular and conical form and a hemispherical part. Present study aims to investigate both experimentally and numerically the deformation behavior, load carrying capacity and energy absorption of a thin-walled bio-inspired structure under quasi-static and dynamic loadings. The applications of such structure may include the crash bumpers of vehicles to absorb the crush energy during a collision and also the core material of sandwiches for the structural protection against blast loading.

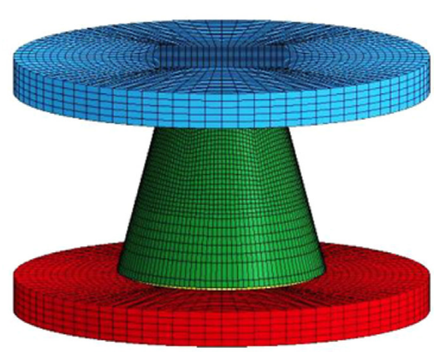
2. Materials and testing

The constituents of the bio-inspired structure were formed by a deep drawing process using an AISI 304L stainless steel blank having 0.5 mm thickness. The deep drawing process was composed of sheet forming and trimming. The sheet forming was accomplished in two stages. The hemispherical cap of the inner core and the flat-top portion of the outer shell were formed in the first stage, while the conical parts of the components having the desired angle, height and diameter were formed in the second stage. The plastic strain in the first stage was below the fracture strain of the blank material and trimming was applied to remove the excess elongations in the skirt and the upper region the outer shell. The top and bottom diameters of the outer shell, the bottom diameter of the core and the height of the both constituents are 15.5, 30, 29 and 24.9 mm, respectively.

The yield strength, elastic modulus and failure strain of AISI 304L stainless steel sheet metal were determined from the tensile tests conducted at quasi-static and high strain rates. The quasi-static tests were performed in a Shimadzu universal test machine in accord with ASTM E8M-04 standard [28]. The axial displacement of the test sample was recorded by a video extensometer. The high strain rate tensile tests were performed in a Split Hopkinson Tension Bar (SHTB). The used SHTB set-up was made of 2 cm-diameter 316 L stainless steel bars, with a striker tube length of 30 cm, incident bar length of 244 cm and transmitter bar length of 244 cm. The elastic modulus, density and yield strength of the bar material are 193 GPa, 8 g cm^{-3} and ~ 300 MPa, respectively. In SHTB test, a gas gun fires a striker tube with an inner diameter of 2 cm and outer diameter of 2.9 cm to the stepped end of the



(a)



(b)

Fig. 2. (a) The model of deep drawing process and (b) compression test model.