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Original Research Article

Absorbed energy by foam-filled quadrangle tubes during the crushing process by considering the interaction effects

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ABSTRACT

In this article, some theoretical relations are derived to predict instantaneous crushing force and absorbed energy during initial fold formation in polyurethane foam-filled quadrangle tubes under the axial crushing load. Theoretical analysis is performed based on the energy method. In the theoretical analysis, crushing wavelength is considered as a constant parameter through the process and as a function of column geometrical dimensions. In the analytical calculations, interaction effects between the polyurethane foam and inner wall of quadrangle tubes are considered and a formula is presented to predict absorbed energy by the interaction effects. In the experiment part, some foam-filled specimens were prepared and axially crushed to obtain experimental diagram of crushing force versus axial displacement. Comparison of the theoretical predictions of crushing force and absorbed energy with corresponding experimental results showed a good agreement. Also, it was found that theoretical predictions by considering the interaction effects have a better correlation respect to the experiments.

1. Introduction

Thin-walled structures such as honeycombs and tubes due to their special features such as fatigue resistance and high strength to weight ratio, are utilized as energy-absorber in different industries of military, aerospace, transportation, construction, and automotive bumpers to dissipate kinetic energy of the dynamic and static external loads. Local buckling or crushing process is taken into consideration in the tubes exposed to axial force and this deformation mode is different from the global buckling. Thin-walled structures absorb a substantial amount of kinetic energy. Therefore, many studies have been carried out on axial deformation of tubes by theoretical, experimental and numerical methods.

Wierzbicki and Abramowicz [1] introduced a kinematics method of plasticity and suitably generalized to large deformation problems to derive a theoretical formula for predicting the average axial force of quadrangle and hexagonal tubes during the crushing process. Reid et al. [2] inspected

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quasi-static and dynamic axial crushing of empty and filled quadrangle tubes by polyurethane foam with various densities, experimentally and theoretically. Santosa et al. [3] performed a comprehensive experimental and numerical study of crushing behavior of aluminum foam-filled sections undergoing axial loading. Hanssen et al. [4] found that optimum foam-filled quadrangle tubes have smaller section dimensions and less weight in comparison with traditionally designed empty tubes. Abramowicz [5] focused on crushing mechanics and its application to calculate and design thin-walled components for optimal impact energy dissipation. Zhao and Abdennadher [6] presented a study on strength enhancement of quadrangle tubes under impact loading. The purpose of the study was to understand impact strength enhancement in a successive crushing process of some cellular structures. Rossi et al. [7] presented results of an optimization study that involves validation and suitability of numerical simulations to predict energy absorption and deformation characteristics of aluminum extruded tubes with different polygonal sections. Zhang and Cheng [8] consummated a comparative study of energy absorption characteristics between foam-filled quadrangle tubes and multi-cell quadrangle tubes by using nonlinear finite element codes LS-DYNA. They found that multi-cell quadrangle tubes are more attractive than foam-filled quadrangle tubes, on the basis of a comparison of collapse modes. Zhang et al. [9] proposed a novel idea by installing a buckling initiator near the impact end of a pre-hit quadrangle tubes and pulling strips; and showed that initial peak force of quadrangle tubes greatly reduces while its deformation mode and excellent energy absorption are retained. Zhang and Huh [10] inspected energy absorption characteristics of longitudinally grooved quadrangle tubes under axial compression by means of explicit nonlinear finite element code LS-DYNA. They introduced the groove as an efficacious way to boost crashworthiness of thin-walled structures. Alavi Nia and Sadeghi [11] studied effects of polyurethane foam-filler in aluminum honeycombs under the axial compression by the experimental method. The tests indicated that existence of foam in panels enhances their energy absorption capacity, mean crushing strength and number of folds. Najafi and Rais-Rohani [12] investigated mechanics of plastic collapse in single-cell and multi-cell tubes by employing nonlinear finite element analysis. Gronostajski et al. [13] revealed that how the structure parameters described by crashworthiness indicators could be calculated for various structures. The effects of crashworthiness parameters of different constructions and profiles on the correlation between energy absorption and maximum collision force were given. Tobota et al. [14] investigated thin-walled cylindrical tubes filled with polyurethane foam under quasi-static and dynamic axial crushing load by experimental and numerical methods. Two types of profiles were used in their study: single-walled and double-walled specimens. They found that crashworthiness ability increases with foam density; and double-walled tubes have greater energy absorbing ability. Hou et al. [15] proposed a numerical virtual model of honeycomb specimens as a small structure to simulate its combined shear-compression behavior under impact loading. It was found that normal strength of honeycombs decreases with increasing shear load. Niknejad et al. [16,17] introduced theoretical relationships to predict instantaneous crushing force of initial fold formation in quadrangle and hexagonal tubes under the axial loading. Review of the previous published works reveals that a theoretical model of deformation has been introduced by Niknejad et al. [18] for predicting mechanical behavior of polyurethane foam-filled quadrangle tubes during the crushing process. According to their model, instantaneous crushing force was predicted. In this model, effects of interaction between the polyurethane foam and inner wall of quadrangle tubes were not taken into account and therefore, comparison of theoretical predictions with the experiments showed a considerable difference. In the present article, a new theoretical formula is derived to predict diagram of axial force versus axial displacement during the crushing process by considering the dissipated energy due to the interaction effects between polyurethane foam and inner wall of the quadrangle tube. Also, some axial compression tests are carried out on foam-filled quadrangle tubes and theoretical predictions are compared with the experimental results.

2. Theoretical background

Niknejad et al. [18] derived a relationship to estimate instantaneous crushing force of polyurethane foam-filled quadrangle tubes versus the crushing angle or axial displacement by the theoretical method. For this purpose, they used the introduced superfolding element by Wierzbicki and Abramowicz [1] as depicted in Fig. 1 and calculated axial force, on the basis of the energy method. In a superfolding element, as a theoretical model of a corner element, three different mechanisms of energy dissipation were taken into account:

Extensional deformation on toroidal surface
Bending around horizontal hinge lines AB and BC
Bending around inclined hinge lines UB and BL.

Abedi et al. [19] derived the ensuing relation to predict absorbed energy rate by the extensional deformation in a superfolding element during the crushing process:

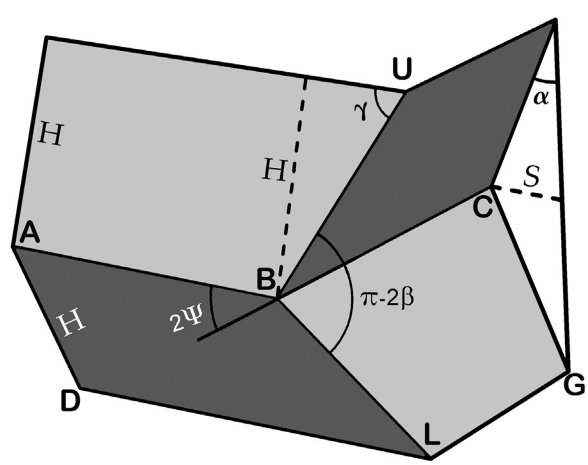

Fig. 1 – A superfolding element.