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Finite element analysis of expanded polystyrene foam under multiple compressive loading and unloading

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In this paper, finite element (FE) simulation of multiple compressive loading and unloading of expanded polystyrene (EPS) foam used in packaging is studied in detail. Results of FEA packages ABAQUS and LS-DYNA are compared to compression test results and cushioning diagrams for multiple loadings. Foam package designers can use crushable foam material model of ABAQUS and low density foam material model (MAT 57) of LS-DYNA to accurately predict maximum deceleration, force, and displacement for first loading, but FEA packages need improvement for the case of unloading and reloading. ABAQUS overpredicts maximum deceleration, force, and displacement for the same amount of absorbed energy at each loading step. LS-DYNA gives more accurate results if parameters for controlling shape and hysteresis of unloading and reloading in MAT 57 are calibrated using test results, but its evaluation of force and displacement in elastic region and residual deformation after unloading should be improved.

1. Introduction

In most energy absorbing applications, foam is loaded only once, and many studies in literature are focused on single loading of foam. Experimental and numerical studies on multiple loading and unloading are very limited. On the other hand, packaged objects such as home appliances can be exposed to multiple impact loadings being in terms of vertical drops during transportation.

There are many studies in literature that present constitutive models and methods for calculating stress–strain and absorbed energy under compressive loading. Liu et al. [1] developed a constitutive model with five parameters that are functions of foam density for compressive loading. In the case of multiple loading, their model is valid only for the plastic region and is not valid for elastic region of the reloading and unloading. Avalle et al. [2] reviewed existing constitutive models for single compressive loading of various foams and validated them by using experimental measurements. They proposed an improved model for single loading only with parameters depending on the foam density. Ozturk and Anlas [3,4] presented how force and deformation change in multiple compressive loading and unloading of polymeric foams, and proposed a phenomenological constitutive model and a method to calculate reaction force, deformation, and absorbed energy for multiple loading and unloading.

The conventional method of designing foam packaging for energy absorption is based on uniform compressive loading, and cushioning diagrams are used for prediction of maximum deceleration during impact [5]. Cushioning diagrams are obtained by plotting impact factor *G* (ratio of maximum deceleration during cushioning to gravity) versus static stress (mass of falling object over supporting foam area) for different foam densities, drop heights, cushion thicknesses, and material densities. The procedure to prepare cushioning diagrams are described in ASTM D 1596–97 [6] and DIN 55471 [7] standards. Measurements for a specific foam density for different foam thicknesses and drop heights require many experimental resources; therefore, researchers have tried to decrease experimental work using analytical models. Ramon and Miltz [8] presented a method to predict cushioning curves for semiflexible polyurethane (PU), closed-cell expanded polystyrene (EPS), and crosslinked polyethylene (PE) using constant-strain rate measurements and analytical evaluations. They showed that cushioning curves could be successfully obtained using a stress–strain curve and their dynamic model for rate independent foams like EPS. Sek et al. [9] proposed a method to determine cushioning curves using data of a single impact test. They studied expanded PU and EPS, and obtained cushioning curves with improved accuracy and reduced testing time. Burgess [10] used a single cushioning curve of expanded PE foam for an arbitrary drop height and foam thickness, and generated all other cushioning curves regardless of drop height, cushion thickness, or static loading. The studies cited above are all for single loading; therefore, their methods are not suitable for packaging applications where

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