Dynamic Response of a Multilayer Corrugated Structure with History-Dependent Properties Subjected to Transient Loads

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ABSTRACT

Composite corrugated- or honeycomb-type multilayer structures are considered for the use as cushioning elements for protection against shocks and vibration. Numerical model for prediction of the dynamic response of such structures to obtain the cushioning response maps and shock response spectrum maps in order to select the optimum static stress is presented, and results of simulations are discussed. Initial deformation characteristics of layers in these composite structures vary, from predominantly elastic to predominantly plastic. At any instant the behaviour of individual layers depends on the recent deformation history and is also being affected by the current behaviour of other layers. The model was developed in Simulink® and the approach was guided by experimental results, including high-speed videography. The model replicates the chaotic behaviour of individual layers and predicted shock pulses are similar to those obtained experimentally.

INTRODUCTION

The paper is concerned with the investigation of behaviour of composite multilayer structures comprising layers of corrugated- or honeycomb-type material when subjected to impacts. It was shown that these structures, with incorporated crumple zone, can be used for improved protection against shocks in transportation packaging, in particular, for extending the range of acceptable impact velocity [1]. An example of such a cushioning structure is shown in Fig. 1, which demonstrates a three- to five-fold reduction of peak acceleration, simply caused by the addition of four smaller virgin layers, two of which have collapsed, although at different locations within the stack. Analysis of shock pulses augmented by videographic observations with a high-speed camera revealed a significant contribution of dynamic effects within the layers of tested material [2,3]. When the weakest layer is collapsing it undergoes a plastic deformation which provokes other layers, still in the elastic range, to expand. However, their compression-relaxation properties will now be affected by their recent history. An effect of this process is a stress wave travelling through the sample, detectable experimentally in the acceleration signal measured at the impactor. The process is not dissimilar to geological earthquake tremors.

Examples of the changes to compression-relaxation characteristics between virgin and precompressed states of corrugated structure are presented in Fig. 2. Thus, the phenomenon is highly nonlinear, and its numerical modelling requires the relevant parameters to be a function of the deformation history. The characteristics will vary from predominantly plastic to mainly elastic.

Layers of the structures considered in this paper may have a different surface area but principally they are made from the same corrugated material. These structures’ main variability is their level of precompression that induces a modification to their initial compression characteristics and the instantaneous characteristics during an impact depends on their immediate history as well as the behaviour of other layers in the stack.

An example of typical compression characteristics for a single layer of corrugated fibreboard is shown in Fig. 3. It is a natural conclusion to consider a numerical model in which the properties of such a layer are all what will be required and that the current properties are determined parametrically during the execution of the model. For
example, in order to determine the initial characteristics of a precompressed layer one need to specify its virgin properties and the strain applied in precompression.

Figure 1. Shock pulses of three composite configurations (drop height 0.3 m): (a) no crumple layers; (b) four crumple layers of 1/3 area across flute machine direction; (c) four crumple layers of 1/3 area along flute machine direction.
Figure 2. Compression-relaxation characteristics of: (a) virgin and (b) precompressed corrugated structure.

Figure 3. Actual compression characteristics of a layer of flute type B corrugated fibreboard at the strain rate of 0.01 s$^{-1}$.
DESCRIPTION OF THE MODEL

Matlab® and Simulink® were chosen as the programming environment to model the uniaxial dynamic behaviour of the multilayer corrugated structures (MCS) in the gravitational field [4,5,6] and a number of Simulink® subsystems were developed (Fig. 4). A generic Single-Degree-of-Freedom (SDOF) system with vibrating base and/or force excitation was programmed as an Ordinary Differential Equation (ODE) in such a way as to enable the simulation of practically any nonlinearity of the spring and the damping element, including the prevention of the viscoelastic linkage to operate in tension in order to simulate, for example laminations losing contact with one another such as during the bouncing induced by vibrations. The complex behaviour of MCS was coded in a parametric fashion and accomplished by defining Simulink's so called s-functions [7]. As illustrated in Fig. 4, two SDOF subsystems were joined to form a model of a single layer of MCS, the bottom spring simulating the contact conditions. An SDOF was adapted to model the platen of a free-fall cushion testing apparatus or alternatively the crossbar of a universal testing machine (UTM). Another subsystem was developed to simulate an actuator of a UTM, capable of various modes of excitation, filtering options, and either acceleration or displacement control. The same subsystem was also used to model a seismic mass. Fragments of an assembled eight-layer structure are shown in Fig. 4.

The central module of the model was the s-function. It was executed at each time step of the ODE solver. It remembered and tracked the history (states) of each layer and modified their original stress-deflection characteristics, imbedded as a cubic spline, depending on the up-to-date exertion of a layer into the plastic region.

Two-stage implicit Runge-Kutta formula with a first stage that is a trapezoidal rule step and a second stage that is a backward differentiation formula of order 2 (TR-BDF2 [7]) was used as the solver of ODEs.

RESULTS

The results presented in this paper are for the simulation of engineered multilayer cushioning structures made of corrugated fibreboard, comprising a stack of five precompressed, and three virgin layers with the contact area 1/3 of the virgin pad and made of the same material, which are aimed to act as sacrificial crumple elements to dissipate the energy in extreme impacts.

In order to verify the model of stress-deflection characteristics of a single layer, a series of numerically simulated progressive compression tests at various strain rates were performed. It was achieved by switching the gravitational field off, assigning infinitely large mass to the platen and using the ramping mode of the actuator in displacement control with a suitably set low-pass filter. Fig. 5 compares characteristics at various ramp speeds between 1 mm/s and 200 mm/s. Experimental investigations have shown that the effect of ramp speed due to increased damping becomes saturated at approximately 200 mm/s. The implemented nonlinear velocity-dependent damping model used an exponentially decaying function to model this saturation. The model automatically modified the initial compression characteristics of a layer after it had been subjected to a precompression strain. The comparison of simulated progressive stress-deflection characteristics at the ramp speed of 2 mm/s obtained for a virgin layer and its modified characteristics after a precompression to 60% strain are illustrated in Fig. 6. A build-up of hysteretic behaviour starts to be more prominently visible, in comparison to the ramp speed of 1 mm/s shown in Fig. 5. The results of numerical experiment emulated favourably the behaviour observed experimentally.

Fig. 8 presents a collection of animation frames showing intralaminar forces and deflections at selected times during the same impact as shown in Fig. 7(a). The impact starts at approximately 0.2 ms mark with the impactor velocity of -3.430 m/s. Particularly interesting is the sequence commencing at 4.333 ms mark that initiates the sudden drop of acceleration which corresponds to the start of collapse of the bottom virgin layer. At the vicinity of 6 ms mark the top virgin layer starts to collapse. The centre layer collapses last at approximately 8 ms mark. Even though the layers are numerically identical the order the layers collapse is chaotic. It was found that the order can be changed by introducing minute variations to the properties of the layers. Each of the collapses causes a sudden drop in the shock acceleration which illustrates the desired effect of crumple layers. Just before 9.867 ms mark the impactor bottomed-in and then reversed its velocity. At 15.8 ms the impactor is subjected to the gravitational acceleration of -9.8 m/s² which indicated the end of impact and the start of the separation from the pad at the velocity of 0.841 m/s. Hence, the coefficient of restitution of this impact was 0.245.
Figure 4. Simulink’s subsystems developed for the numerical model, an example of their connectivity and a dialog box for a layer (the dialog box can be filled programmatically).
Figure 5. Simulated progressive compression characteristics of a single corrugated layer at various strain rates obtained from the model.

Figure 6. Initial compression characteristics of a corrugated layer after being precompressed to 60% strain compared to progressive compression of a virgin layer (at 2 mm/s).

Figure 7. (a)-Predicted shock pulse; and (b)-Its shock response spectrum (initial precompression strain of 45%, static stress 1.6kPa, platen drop height 0.6m).
Figure 8 (part 1). Animation frames showing intralaminar forces and deflections at selected times during the impact in Fig. 7(a). (Note: The relevant times are above images. The colour bar is on the next page).
One of outcomes from the simulations is the information regarding optimum static stress with respect to minimisation of the shock transmitted to the impactor; the other is its shock response spectrum to suggest a range of modal frequencies that may produce elevated shock amplification. The model can obtain this information in running in the batch mode in the form of cushioning maps and shock response spectral maps. Fig. 9 and Fig. 10 present such maps for the case of precompression strain of 45% and 75%, respectively. It is evident that the lowest shock occurs for the static stress of approximately 1.3 kPa, which corresponds to Fig. 8.
Figure 9. Cushioning and shock response spectral maps at 45% precompression strain.

Figure 10 (part 1) Cushioning and shock response spectral maps and 75% precompression strain.
CONCLUSIONS

The model presented in the paper confirms the chaotic nature of dynamic compression a corrugated multilayer structure exhibits when subjected to transient loads, and offers an insight into this process otherwise difficult to obtain experimentally. The uniaxial numerical model is parametric and highly nonlinear and handles history dependent parameters during impacts. The model produces results compatible with observations obtained with high-speed videography. Results provided by the model assist in engineering an optimum solution for a cushioning system that utilises collapsible layers.

REFERENCES