JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 39, No. 6, November–December 2002

Finite Element Modeling of the Axial Collapse of Foam-Filled Structures

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Recent developments in the manufacturing of economical closed-cell aluminum foam have led to increased interest in the use of the foam as a filler in energy-absorbing thin-walled ultralight structures. Foams are ideal energy absorbers because they can undergo large deformations at nearly constant stress. In addition, the presence of the filler material leads to a modification of the mode of collapse of the structure, thereby increasing the specific energy absorption of the composite structure. We present a method for modeling the quasi-static axial collapse of foam-filled aluminum tubes using LS-DYNA. In this case, the tube was modeled using shell elements, and the foam was modeled using solid elements. The interface between the filler and the tube was modeled using contact elements. Three aspects of axial crushing of foam-filled structures were examined: the effect of foam density, the wall thickness, and the width of the tube. The results reveal an increase in the specific energy absorption of up to 35%.

Nomenclature

C	=	proportionality constant
c	=	tube wall width
E	=	elastic modulus
e_E	=	true elastic strain
e_P	=	true plastic strain
e_T	=	true total strain
F_m	=	experimental crush load of empty column
$F_{m,f}$	=	crush load of foam-filled square column
H	=	half-height of fold
h	=	tube wall thickness
n	=	power fit exponent
P_f	=	property of interest
p	=	hydrostatic pressure
ε	=	engineering strain
ρ_f	=	density of foam
ρ_s	=	density of solid material
σ	=	engineering stress
σ_e	=	von Mises equivalent stress
σ_f	=	skeletal cube model flow stress
σ_T	=	true stress
σ_y	=	initial yield stress
σ_0	=	cell wall flow stress

I. Introduction

VEHICLE crashworthiness depends on the structural properties, the interior design, and the restraint components of the mobile system. During collision/impact, the energy of the crash and the manner in which these loads are transmitted through the system will determine the extent of damage to the contents. The amount of energy that can be absorbed by the vehicle is paramount because this will directly affect the magnitude of the forces felt by the occupants. Therefore, the purpose of the use of a crashworthy design system is to dissipate the kinetic energy of the impact in a controllable manner, to retain a survival space for the occupants, and to minimize the forces and accelerations experienced by the occupants.

Two major concerns in the design of components for crashworthiness are the ability to predict the mode of collapse for a component and the repeatability of the mode of collapse. In the case of new designs incorporating aluminum, the ability to model the mode of collapse is complicated by the vast majority of crashworthiness literature being on the performance of mild steel structures. An example of a material-related instability was presented by McGregor et al.[1] They noted that an AA6082 aluminum box column exhibited a stable progressive collapse when in the T4 temper, but that the mode of failure changed to fracture when taken to the T6 condition due to the limited ductility of the age hardened material. This highlights one of the concerns of using new materials for crash components without adequate analysis and testing.

II. Theoretical Considerations

In this section, the following topics are addressed: collapse of thin-walled structures, mechanical characteristics of foam materials, and foam-filled structures.

A. Collapse of Thin-Walled Structures

The problem of plastic axial collapse of thin-walled structures had already been discussed in a paper by Wierzbicki and Abramowicz.[2] They developed a method for determining the mean crush load of a corner element using a kinematically admissible velocity field. Abramowicz and Jones[3] further developed this methodology and found good agreement with experimental results conducted on tubes of mild steel. The progressive collapse of a square tube can be idealized as the collapse of a layer of "superfolding" elements, shown schematically in Fig. 1.

Four modes of deformation are predicted by these collapse elements: one symmetric mode, two asymmetric modes, and an extensional mode of deformation. In the symmetric mode of deformation, shown in Fig. 1a, two lobes on opposite sides of the tube fold outward, and the remaining two sides fold inward. The symmetric mode consists of one layer of four type-1 collapse elements.

The fold length for the symmetric mode is given in Ref. 4 by

$$H = 0.99c^{\frac{2}{3}}h^{\frac{1}{3}} \tag{1}$$

The two asymmetric modes of deformation have been observed experimentally for the axial crush of square tubes, namely, mixed mode A and mixed mode B. Mixed mode A consists of two layers (total height $4H$) with six type-1 and two type-2 basic folding elements, whereas mixed mode B consists of two layers with seven type-1 and two type-2 basic folding elements.

Received 21 June 2001; revision received 24 June 2002; accepted for publication 17 July 2002.

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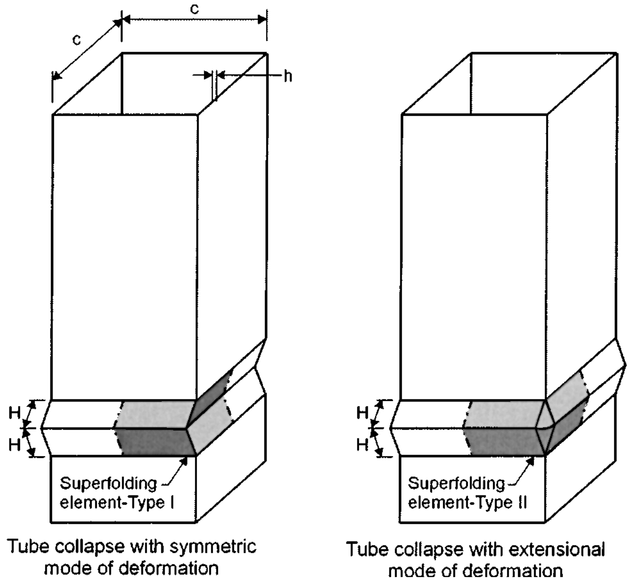

Fig. 1 Axial collapse of box column a) symmetric mode with layer of four type-1 elements and b) extensional mode with layer of four type-2 elements.

The extensional mode of deformation, shown in Fig. 1b, involves a collapse layer consisting of four type-2 folding elements. Because of the large amount of membrane stretching in this mode, the mean load is higher.[5]

Generally, the exact mode of deformation is difficult to predict because imperfections in the geometry influence the initial buckling. However, experimental work using mild steel specimens showed that the extensional mode dominates for $c/h \leq 7.5$, whereas for $c/h \geq 40.8$ the symmetric mode is prevalent. Between the two values, asymmetric mixed mode B occurs. The static progressive buckling of square tubes with asymmetric mode B or symmetric mode are virtually indistinguishable from a practical point of view.[5]

Langseth and Hopperstad[6] and Langseth et al.[7] performed experimental and finite element work on the static and dynamic axial crushing of thin-walled aluminum extrusions. They examined 6060-T4 and 6060-T6 square tubes with $32 \leq c/h \leq 44.4$. They found that, for quasi-static loading, the extrusions always exhibited a symmetric mode of deformation, with the lobe fold length being a function of the temper.

B. Characterization of Foam Materials

Cellular materials exhibit high specific stiffnesses and, therefore, are ideal for low-weight structures. These materials are also popular as construction materials, as well as in engineered structures. Foams possess very unique mechanical properties when compared with solid materials. Metallic foams have been manufactured from aluminum, zinc, and iron and can have relative densities as low as 3% when compared to the fully dense material.

The use of metallic foams as energy absorption devices leads to a desire to understand the plastic collapse behavior of these materials under multiaxial loading conditions and the subsequent plastic flow behavior. As illustrated in Fig. 2 (see also Ref. 8), the compression response exhibits three distinct regions. The first is a roughly linear elastic regime. This region is followed by a long stress plateau, where the stress remains nearly constant. At a large value of strain (typically 0.6–0.9, depending on foam density), the stress starts to rise steeply with a small increase in strain. This region of the compression curve is called densification. Another observation from the compression response of foams is that foams exhibit a Poisson's ratio of near zero in the plastic region.

Gibson and Ashby have conducted a significant amount of work on the mechanical behavior of cellular structures.[9] They have shown that the mechanical properties of cellular materials are heavily dependent on the relative density of the cellular material. They argued that the properties of foam follow a power law of the form

$$P_f = C(\rho_f/\rho_s)^n \tag{2}$$

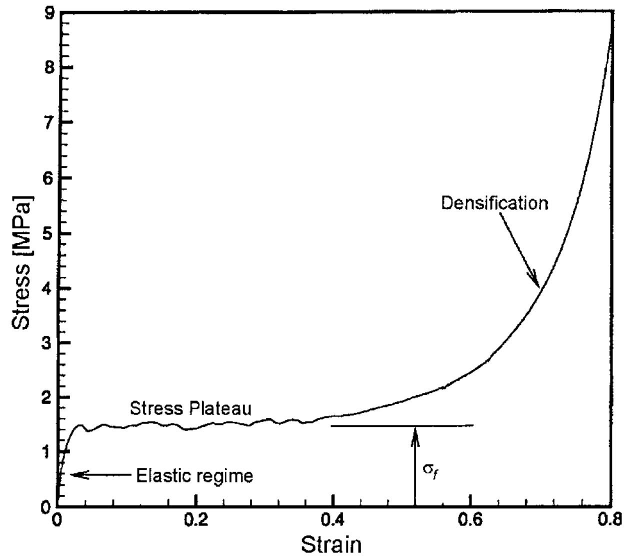

Fig. 2 Typical compression response of an aluminum closed-cell foam.[8]

The exponent n usually has a numerical value between 1.5 and 2.0.

In crashworthiness applications, the uniaxial foam flow stress is usually the quantity of interest. Gibson and Ashby[9] found that the flow stress of a metallic foam, based on the initial bending collapse of a skeletal cube model, was equal to

$$\sigma_f = 0.3\sigma_y(\rho_f/\rho_s)^{1.5} \tag{3}$$

In contrast to this, Santosa and Wierzbicki[10] found that a uniaxial foam flow stress could be determined by

$$\sigma_f = 1.05\sigma_0(\rho_f/\rho_s)^{1.5} \tag{4}$$

when using a kinematic plasticity folding analysis to model a closed-cell foam. They compared Eq. (4) with the results of closed-cell aluminum foam and found excellent agreement. However, the cell-wall flow stress σ_0 was selected to provide a best fit because the true flow stress of the cell-wall material was not known.

Gibson et al.[11] developed a yield surface for the multiaxial loading of metallic foam. They proposed the following yield envelope:

$$\sigma_e/\sigma_f + 0.81(\rho_f/\rho_s)(p/\sigma_f)^2 = 1 \tag{5}$$

where σ_f is given by Eq. (3).

Miller[8] also conducted work on the multiaxial yield envelope for metallic foams. He noted that the model proposed by Gibson and Ashby[9] would yield a plastic Poisson's ratio of 0.47 for large plastic deformations, which is clearly not in agreement with experimental observation.

C. Foam-Filled Structures

In addition to the energy that can be absorbed by the foam alone, its presence as a filler material leads to a modification of the mode of collapse of the composite structure, thereby increasing the energy absorption of that structure. This increased energy absorption is illustrated in Fig. 3, where the interaction results in greater crush loads, as well as in an increased number of peaks relating to the number of folds.

The effect of foam filling on the collapse of metallic thin-walled structures was first studied for polyurethane foam. Thornton[12] conducted extensive quasi-static and dynamic compression of polyurethane-foam-filled thin-walled sections. He concluded that polyurethane foam filling was not weight effective, unless relatively thin sections made of high-density low-strength alloy, that is, mild steel, were used.

With the recent introduction of economical foams manufactured from aluminum, interest in foam filling for structural collapse was renewed. Much higher collapse loads are possible with aluminum

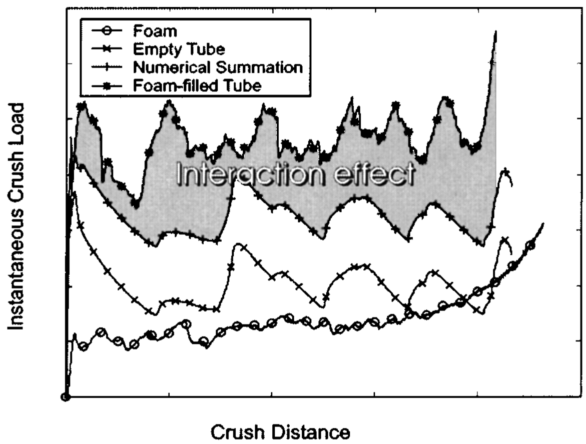

Fig. 3 Interaction of thin-walled column and foam.

foam because of the higher strength of the bulk material when compared to polyurethane.

The first study of the axial quasi-static compression of aluminum foam-filled tubes was conducted by Seitzberger et al.[13] They examined RSt37 steel square and round tubes filled with aluminum foam using a powdered metallurgy process. The foam densities were in the range of 0.47–0.7 g/cm^3. They found that an increase in specific energy absorption of 40–60% could be realized by aluminum foam filling. The square tubes collapsed with a symmetrical mode of deformation; the wavelength of the folds was smaller, but a more irregular folding pattern was observed than with the empty tubes. They also presented finite element (FE) analysis of the compression of foam-filled square tubes using a foam material model based on the analytical results of Gibson and Ashby.[9] The analytical results showed a similar change in deformation mode, and the predicted mean load agreed reasonably well with their experimental work.

Hanssen et al.[14] conducted quasi-static crushing of square AA6060-T4 and AA6082-T4 aluminum extrusions with foam densities of 0.15–0.50 g/cm^3. Tubes with widths of 80–160 mm were used with $41 \leq c/h \leq 80$. They explored both bonded and unbonded specimens. They found that the foam filling increased the number of lobes formed during crush and that the number of lobes was a function of foam density. They also found that bonding the foam could induce extensional fold formations with an increase in specific energy absorption of 6–45%. However, many of the higher strength AA6082 specimens ruptured with lower energy absorption. This possibility of rupture led them to caution that strict requirements need to be placed on the properties of the extrusion material if bonding is to be used. They developed an empirical relationship based on the experimental results for foam-filled square columns, given by

$$F_{m,f} = F_m + c^2\sigma_f + 5ch\sqrt{\sigma_f \sigma_0} \qquad (6)$$

where the first term represents the experimental crush load for an empty column, the second term is the uniaxial contribution of the foam filling, and the last term accounts for the interaction effect.

III. FE Modeling

In this section, the FE model used in the accurate simulation of the quasi-static axial collapse of foam-filled box columns is discussed. The geometry to be modeled is shown in Fig. 4, along with some of the numerical modeling considerations that need to be outlined. The geometry consists of a square tube of width c and thickness h. The length L of the tube was selected to be 300 mm, so that it could capture the desired folding mechanism without being influenced by boundary effects. Preliminary calculations using Eq. (1) showed that a minimum of five folds should result for the case of an empty tube of this length, for the range of parameters considered in this study. Further details are provided in Ref. 15.

The tube was filled with a foam-filler material with an initial gap between the foam and tube of 0.1 mm. The material used for the column wall was aluminum alloy 6061-T4. The relative foam densities used (defined as the ratio between the density of the foam to the density of the solid from which the foam is made) were 3, 5.4, and 10%.

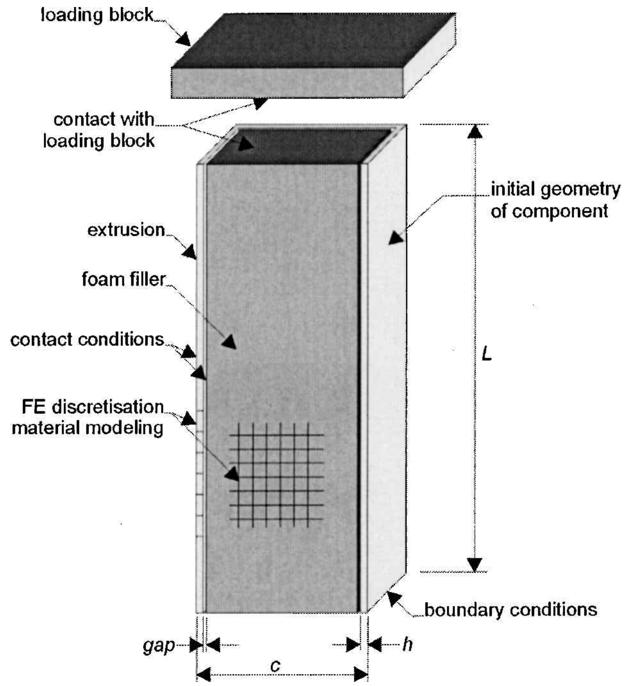

Fig. 4 Cross section of structure to be modeled and FE considerations.

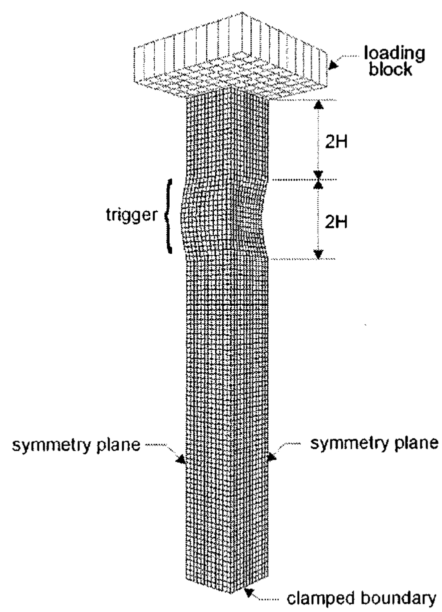

Fig. 5 Three-dimensional FE mesh: exterior view with exaggerated trigger.

Earlier experimental studies[6] have shown that a symmetric mode of collapse is observed for the static axial crush of AA6060 aluminum box columns for $32 \leq c/h \leq 44.4$, regardless of the material temper condition.

The material selected for this study is aluminum alloy 6061-T4. In spite of its lower strength, the T4 condition is typically selected for energy-absorbing components because of its much greater ductility vs the T6 condition. The presence of the foam filler was expected to shorten the fold length of the collapse process, leading to larger strains, and required a material of high ductility if global rupture was to be avoided.

Because a symmetric mode of deformation is expected for this material and geometry, only one-quarter of the tube is modeled, using symmetry. The three-dimensional FE mesh developed is shown in Fig. 5.

A. Details of the Mesh

Belytschko–Lin–Tsay shell elements were used to model the column wall using LS-DYNA. Six integration points were used through the thickness and one integration point in the plane of the elements. As with all reduced integration elements, hourglass control is required to eliminate spurious zero-energy modes in the solution. An eight-node solid element with one-point reduced integration is used to model the foam material. The interface between the foam and column wall was modeled with an automatic surface-to-surface algorithm. Single surface contact was applied to the column walls to avoid interpenetration of the folds generated during axial collapse. Finally, node-to-surface contact was used between the top surface of the column and the rigid striker. These contact types utilize a penalty formulation. A trigger that mimics the geometry of only the first fold was implemented.

B. Constitutive Modeling of Materials

The column walls were modeled using an elastoplastic material model with isotropic hardening and von Mises yield criterion. The material model allows for the input of an arbitrary stress–strain curve using effective plastic strain and effective plastic stress pairs, which are used to form a piecewise linear yield envelope.

To determine the plastic strain, true yield stress values from the engineering stress–strain data, the following relationships were used:

$$e_T = \ln(\varepsilon + 1) \tag{7}$$

$$\sigma_T = \sigma(\varepsilon + 1) \tag{8}$$

$$e_P = e_T - e_E, \qquad e_E = \sigma_T / E \tag{9}$$

The formulas are valid only up to the strain associated with the ultimate tensile stress because, beyond this point, inhomogeneous plastic straining occurs.

The uniaxial true stress, plastic strain curve was used to represent the von Mises yield, equivalent plastic strain relationship. Engineering stress–strain data for aluminum alloy 6061-T4 under uniaxial loading were obtained from Alcan Research Centre, as follows: Young's modulus $E = 70$ GPa, initial yield stress $\sigma_y = 145$ MPa, Poisson's ratio $v = 0.334$, and power law exponent $n = 0.13$.

Because there is no interaction of the stress components in the material model used for the foam, the plastic Poisson's ratio is, by deduction, zero. Thus, for an isotropic foam, the uniaxial stress–strain curve is used for the yield curves governing the normal stress components.

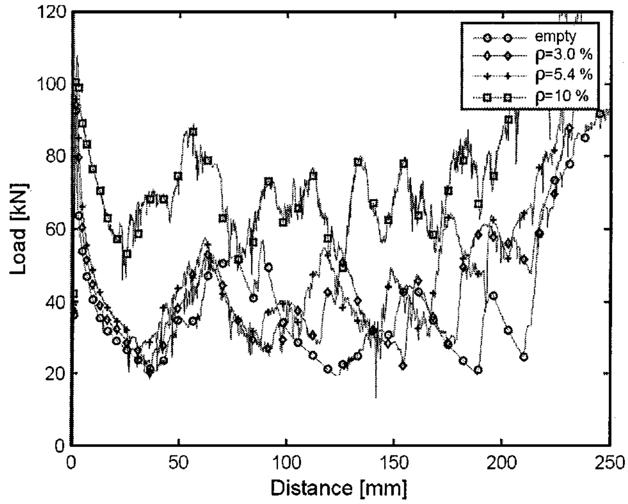

Fig. 6 Instantaneous collapse loads for 75 × 2.5 mm column for various foam densities.

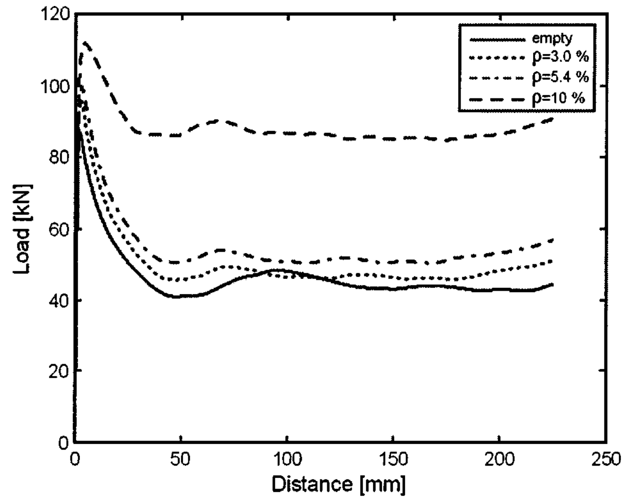

Fig. 7 Mean collapse loads for 75 × 2.5 mm column for various foam densities.

IV. Results and Discussion

This section is devoted to the analysis and discussion of the results obtained from the elasto-plastic quasi-static three-dimensional FE investigations. It addresses 1) the plastic collapse of foam-filled square box columns of varying dimensions and 2) the validation of the FE predictions with the experimental findings.

A. Effect of Foam Density

Figure 6 shows the collapse of fully filled box columns at different displacements for 3, 5.4, and 10% density foams, respectively. The results reveal the following. First, the presence of the foam filler shortens the fold length, resulting in folds of larger curvature. As illustrated by the local peaks in the instantaneous load in Fig. 6, the 10% density foam increases the number of folds from 6 to 10 compared to the unfilled case. Second, the mean collapse load and energy absorbed increases with increasing foam density. Third, the increase in density shortens the effective stroke length of the composite column.

The corresponding mean collapse load can be found in Fig. 7. It is obvious from Fig. 7 that the 10% foam offers the most significant increase in the mean collapse load. The initial collapse of the filled columns is also higher than that for the empty column and is a function of foam density.

B. Effect of Column Geometry

Several runs were performed on the quasi-static crush characteristics of square box columns filled with 10% density aluminum foam. Thicknesses of 2, 2.5, and 3 mm and widths of 60, 75, and 90 mm were considered. The same triggering was applied as that adopted for the foam-filled models but with no filler material. As expected, the results show that the wall thickness of the tube has a significant influence on the mean crush load of the tube, whereas the width of the tube has little influence on that load. On the other hand, the width of the tube has a dramatic effect on the initial collapse load. For example, the collapse load for the 90-mm-wide tube is approximately 50% higher than the collapse load of the 60-mm tube.

C. Validation

Validation of the FE model was carried out in comparison with quasi-static physical tests. Box columns, 76 mm square, 300 mm high, and having a 3-mm wall thickness, were tested both empty and filled with 10% density foam. Material property data for the columns were obtained through carrying out uniaxial tension tests on samples of the column material. In both the overall deformation and number of folds, the predictions matched the experimental data. The mean collapse loads for the validation cases are shown in Fig. 8. In both cases, the FE predictions slightly overestimated the initial collapse load. This is attributed to the FE model assumption of an ideal structure, which is seldom the reality due to geometric and material imperfections. However, overall agreement is excellent, with the FE prediction of the mean collapse load at 200 mm being within 6% of the experimental data.

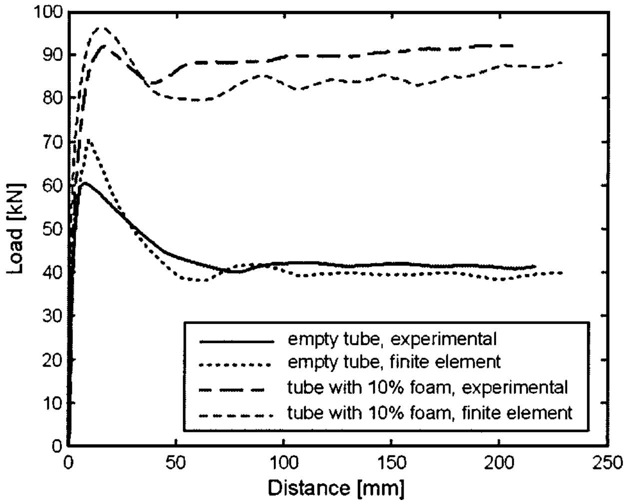

Fig. 8 Comparison between FE predictions and experimental results of mean collapse load.

V. Conclusions

The developed three-dimensional FE model was able to capture accurately the mode of collapse of quasi-statically loaded foam-filled box columns. The column walls were modeled using shell elements, and the column wall material was modeled using an elastoplastic material model with isotropic hardening and the von Mises yield criterion. The box column was given an initial imperfection in the form of a cosine-shaped trigger to initiate the mode of collapse observed in testing.

The effects of column wall thickness, column width, and foam density on the energy absorption of quasi-statically loaded foam-filled box columns were explored. From several FE results, the following conclusions can be made. The first is that the collapse load increases with foam strength, which is an obvious result. For the foams examined in this study, only the 10% foam showed an increase in the specific energy absorption, which indicates that there is a minimum foam density for which foam filling is effective. The largest change in the mean load and specific energy absorption occurred with the thinnest tube, with the width being held constant. This result is due to the strength of the empty column being low compared to the thicker tubes.

Acknowledgments

The financial support provided by Materials and Manufacturing Ontario and the Natural Sciences and Engineering Research Council of Canada is gratefully acknowledged.

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