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Crushing Simulation of Foam-Filled Aluminium Tubes

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A numerical study is presented in this paper to investigate the energy absorption of foam-filled aluminium tubes during crushing. The post-buckling mode of the foam-tube structures has been successfully simulated. The predicted compressive load-displacement is in a good agreement with experimental results. The energy absorption ability of the composite structure due to plastic deformation in a crushing process is evaluated by comparison with the tube structure without foam. The results indicate that the energy absorption of a foam-filled tube structure is superior to the tube without foam. The influences of the friction and the geometric parameters of the structure on the energy absorption have also been investigated. Results from this study will assist automotive industry to design crashworthy components based on foam-filled tubes.
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1. Introduction

Thin-walled metallic tubes have been applied as energy absorbers because of their progressive buckling under axial compressive loading and the lightness of the structure.[1)] According to previous investigations, thin-walled circular tubes can collapse in axisymmetric mode, also known as concertina or ring mode, non-axisymmetric mode, also known as diamond mode, or mixed mode. In which mode a tube crushes largely depends on the geometry of the tube.[2)] Energy will be absorbed through the progressive buckling of the structure.

On the other hand, cellular structures such as honeycombs and foams were also considered as suitable materials for energy absorption. These foam materials show a distinct plateau of almost constant stress in the uniaxial compressive stress-strain curve with the nominal strain value up to 80%,[3)] which indicates a high energy absorption capacity. Recent efforts have been made to combine the two members by taking their advantages to develop foam-filled tubular structures.[4–10)] The experimental results by Reddy and Wall indicates that polyurethane foam filled in metal tubes stabilized the irregular buckling pattern of the empty cylinders and led to the improvement of energy absorption.[4)] Reid believed that steel tubes filled with polyurethane foam is an efficient energy absorbing device.[5)] Seitzberger *et al.* investigated the structure of steel tubes filled with aluminium foam and they have shown considerable mass efficiency improvements with respect to energy absorption.[6,7)] Hanssen *et al.* studied the behaviour of square aluminium extrusions filled with aluminium foam under static and dynamic loading conditions.[8,9)] Recently, Yamada *et al.* did experimental tests to investigate the crushing behaviour and energy absorption of aluminium foam filled aluminium circular tubes.[10)] Aluminium foams are considered as attractive foam filler due to development of cost-effective production processes.

Experimental study on the crushing of aluminium foam-filled aluminium alloy tubes indicates that the crushing behaviour of the tubular structures changed due to foam filling and the energy absorption of the foam filled tubular structures was improved significantly.[10)] The crushing forces of foam-filled tubes are higher than the algebraic sum of the crushing forces of tube and foam itself, resulting from the interaction effect. To understand the mechanism of the improvement of the energy absorption for a foam-filled circular aluminium tube, numerical simulation of the crushing of the composite structure was carried out in this study. The influence of designable parameters on the energy absorption of the structure has been examined. The predicted results would assist the design of foam-filled tubular crashworthy components and stimulate their application in automotive engineering.

2. Numerical Model

Although empty thin-walled tube may deform in a progressive non-axisymmetric manner via the diamond mode, all the aluminium foam filled tubes in the experiments failed in a progressive axisymmetric manner via the concertina mode.[10)] Therefore, we only consider the concertina crushing mode in our current study, which means that we can simulate the physical problem as an axisymmetric one in our modeling. Figure 1 shows the axisymmetric model. Axial loading is simulated by applying displacement on a rigid plate which lies on the top end of the structure while the bottom is constrained to the ground. In previous experimental study,[10)] the crushing was carried out by applying compressive displacement at one end with a fixed strain rate of $10^{-3}\,s^{-1}$. Therefore, we can consider it as a quasi-static problem in our modelling.

The materials used for the simulation were taken based on the experimental study.[10)] The tube is an annealed aluminium Alloy A6063T5 with the Young's modulus of 68.9 GPa, yield stress of 48 MPa and the Poisson's ratio of 0.33. The plastic behaviour of the tube was considered as isotropic hardening

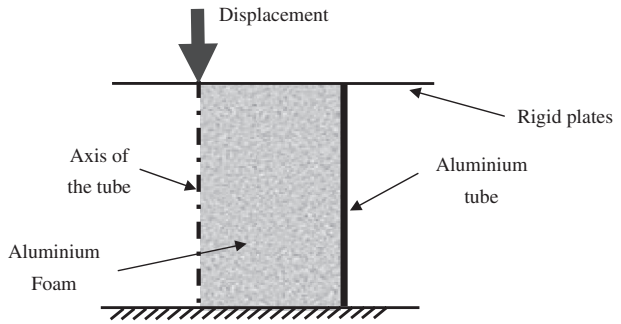

Fig. 1 Illustration of the crushing simulation model of a circular aluminium tube filled with aluminium foam.

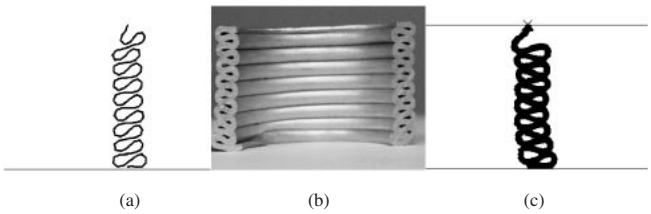

Fig. 2 Comparison of crushed shapes of empty tubes (a) shell-element simulation, (b) experiment and (c) solid-element simulation.

and the hardening data were calibrated from uniaxial compressive test curves.[10)]

In previous experimental study,[10)] the aluminium foam samples have closed-cell structure. The average cell diameter is about 4.0 mm, which is much smaller than the dimension of the structure. It would be much more complicated and computationally difficult to simulate the irregular foam cells explicitly. Instead, we treat the foam as an isotropic homogeneous material based on previous research on foam materials. Such simplified material model should be easier to use for industrial partners. The relative density of the foam $\bar{\rho}$, defined as the fraction of space occupied by the solid, is determined by the porosity P_r,

$$\bar{\rho} = \frac{\rho_f}{\rho_a} = (1 - P_r), \tag{1}$$

where ρ_f and ρ_a are the densities of the foam and the aluminium solid, respectively. The Young's Modulus of the foam, E_f, can be estimated from the relative density by[11)]

$$E_f = A \cdot E_a \cdot \bar{\rho}^2 \tag{2}$$

where E_a is the Young's modulus of the aluminium solid. The porosity P_r was taken as 91.5% to estimate the relative density $\bar{\rho}$. Experimental results indicate that the Poisson's ratio of aluminium closed cell foams under compression varies from 0.13 to 0.4.[12)] In our simulations, the Poisson's ratio was chosen as 0.3. Results from experimental compression tests on foam samples[10)] were utilized to calibrate the plastic behavior of the foam and the coefficient A, which is 0.3.

The crushable foam model with isotropic hardening developed by Deshpande and Fleck[13)] was applied to simulate the plasticity of the aluminium foam. According to the material model, the yield function is

$$\sqrt{\frac{\sigma_{eq}^2 + \alpha^2 \sigma_m^2}{1 + (\alpha/3)^2}} - Y = 0 \tag{3}$$

where σ_{eq} is the Von Mises equivalent stress, σ_m is the mean stress, Y is the hardening material function and α is the shape factor of the yield surface. The hardening function Y is determined from the uniaxial compressive test for the foam[10)] and the value of α was chosen as 1.58.[13)]

The commercial finite element (FE) software package ABAQUS is applied to simulate the crushing of the composite structure under quasi-static loading condition. Due to the small thickness of the tubes, shell elements were initially chosen to simulate the tubes, which can effective and accurately simulate the crushing of the tubes without foam, *i.e.*, empty tubes.[14)] However, when shell elements were applied to simulate the foam-filled tube with 4-node solid elements for the foam, the contact interaction between the tube and the foam caused numerical difficulties. Eventually, that drove us to choose 4-node solid elements for both components. In a typical FE model, four thousands elements were used for the foam and nine hundred elements for the tube. Adaptive mesh is applied to avoid large mesh distortion and maintain a high-quality mesh throughout the crushing simulation. Interactions between the edges of the foam, the walls of the tube and between the foam and the tube were simulated. The duration of the complete crushing calculation for a foam-filled tube is about 7 hours in a SGI Altix supercomputer.

3. Results and Discussion

3.1 Empty tubes and foam samples

For the purpose of the verification of our FE model and material models, the crushing of empty tubes and the compressing of foam without tube were first simulated. Figure 2 shows the final crushed shape of an empty tube, compared with experimental observation. Both shell elements and solid elements were applied in the modeling. Both of the elements can successfully simulate the crushed shape, which is characterized by the folds and is similar to the experimental result. Figure 3 shows the process of the fold forming during the compressive loading from one of our simulations. The first fold appears at the level of the upper plate. After that the folds are generated in the bottom plate.

Figure 4 shows the curve of the reaction load versus the applied displacement from our simulation, compared with experimental result. In this simulation, the length of the tube is 240 mm, the diameter is 80 mm and the thickness is 3 mm, which are identical to the dimensions of the experimental sample. The load-displacement curves are characterized by the peaks. Each peak corresponds to the forming of one fold during the crush. The numerical curve agrees well with the experiment result.

As described in Section 2, we simplified the foam as an isotropic homogeneous material instead of modeling the complicated cell structures in the foam. The constitutive law of the idealized material is taken from Deshpande and Fleck.[13)] For the purpose of verification, we simulated the crush of a foam without tube and compared with exper-

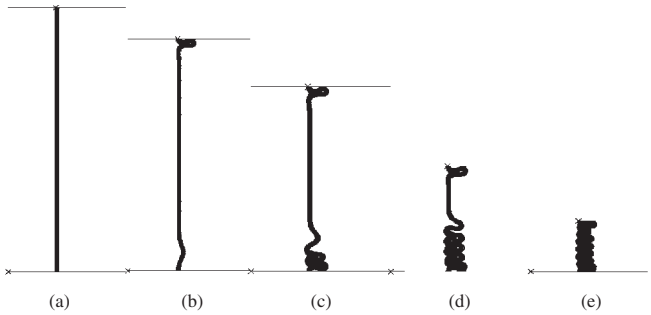

Fig. 3 Simulated progressive buckling of an empty tube from (a) to (e) during the compressive loading process.

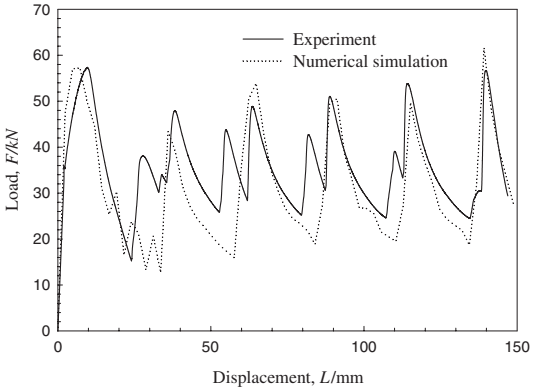

Fig. 4 Comparison of the crushing load-displacement curves of empty tubes between experiment and numerical simulation.

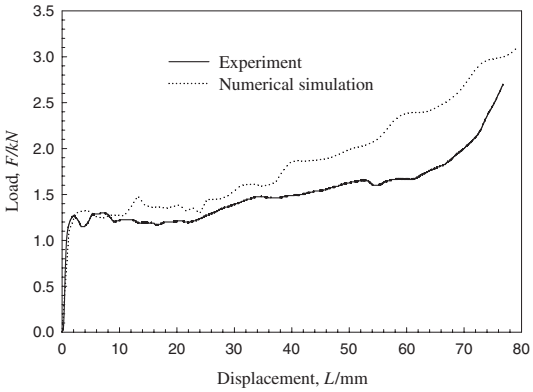

Fig. 5 Comparison of the uni-axial compression responses of a foam sample between experiment and numerical simulation.

imental test. The foam sample has a porosity of 91.5%. The diameter is 37.7 mm and the length is 120 mm. Experiment has been carried out on the same sample under uniaxial compression. Figure 5 shows the comparison of the load-displacement curves between experiment and numerical simulation. The numerical curve successfully produced the irregular crushing behavior although the predicted load in the plastic stage is a little higher than the experimental result. Considering the complexity of the cell structures in the foam, the comparison indicates that the simplified material model can simulate the crush of the foam reasonably well.

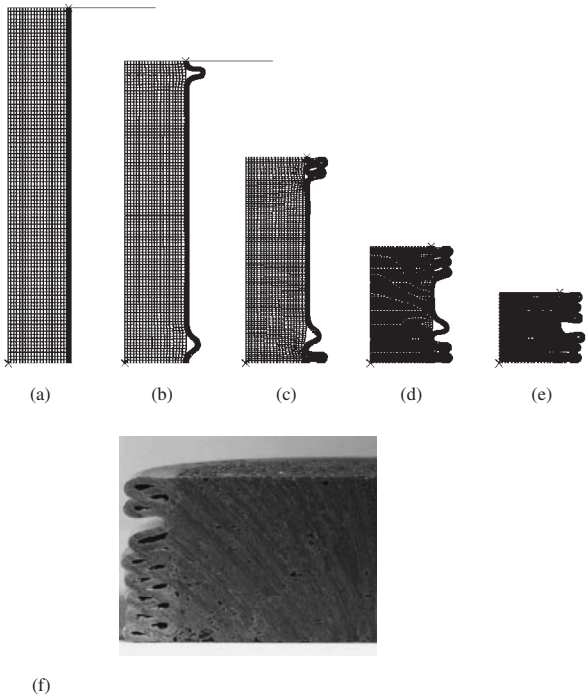

Fig. 6 Progressive buckling of a foam-filled tube from (a) to (e) during the compressive loading process, compared with experimental observation at the final stage (f).

3.2 Tubes with filled foam

Now we can consider the thin-walled circular aluminium tubes filled with aluminium foam. Figure 6 shows the progressive buckling of a sample from our simulation. As we can see, the folds initiate from both end of the tube. After one fold crushes, another fold appears until no more folds can form. Large compressive deformation also occurs in the foam. Similar shape of the folds has been observed from experimental tests, as shown in Fig. 6(f). In this case, our numerical simulation also produced a gap appearing in the middle of the folded tube.

The dashed line in Fig. 7 shows the load-displacement curve for a foam-filled tube from our simulation. This curve is characterized with several peak loads. Each one of them corresponds to the appearance of a fold on the aluminium tube, see Fig. 6. The solid line in Fig. 7 represents the experimental result from the same sample. As we can see, the patterns of the two curves are quite similar although there are some differences between the curves. These differences might due to two major reasons. First, buckling is very sensitive to imperfection. Even the experimental results from different samples with identical dimensions can have huge difference. Secondly, there are many unknown about the interaction between the foam and the tube, which have not completely described in the model.

To understand the effect of the foam on the post-buckling response of the structure, we also plotted the simulated load-displacement curves in Fig. 8 from an empty tube and the tube filled with foam. Both of the curves have similar post-buckling shapes. It clearly indicates that the tube with foam can resist higher load. This is due to the fact that the foam-filled tube is stiffer. The energy absorption E_A during a crush can be calculated as

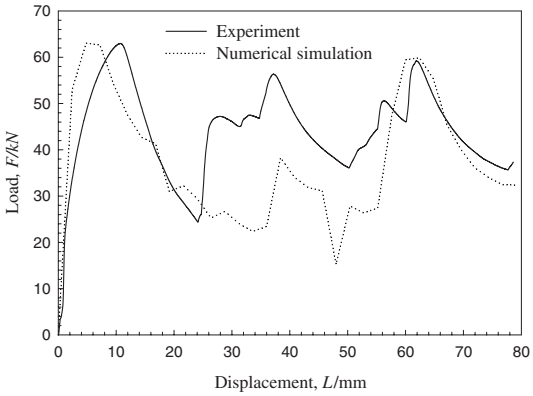

Fig. 7 Simulated crushing load-displacement curve of a foam-filled tube, compared with experimental result.

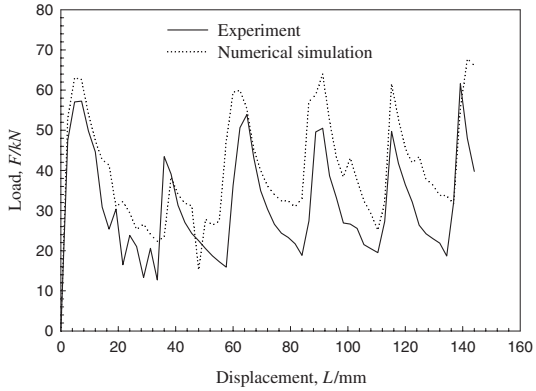

Fig. 8 Simulated crushing load-displacement curve of a foam-filled tube, compared with the tube without foam.

Table 1 All the parameters involved in the crushing simulations.

Material properties		Geometric parameters	Other parameters
Tube	Foam		
Young's modulus: E_t	Young's modulus: E_f	Lenght: L	Friction coefficient between the tube and the foam: f
Poisson's ratio: ν_t	Poisson's ratio: ν_f	Diameter: D	Displacement: U
Yield Stress: σ_{Yt}	Shape factor of the yield surface: α	Thickness: t	
Hardening coefficient: n	Hardening function: Y		

$$E_A = \int F(U)dU \tag{4}$$

where F is the applied load and U is the corresponding displacement. E_A equals to the area between the abscissa and the curve in Figs. 8, which represents the energy absorbed by the structure due to its plastic deformation. In terms of the application of crashworthy components, the larger E_A is, the better is the energy absorption capacity of the structure. Based on Fig. 8 and eq. (4), we can estimate that the energy absorption has been improved from 4.5 KJ to 6.0 KJ after filling the tube with the foam. If we consider the foam-filled tube alone, we can calculate that the tube absorbed the energy of 4.58 KJ and the foam 1.27 KJ. This result confirms the fact that the energy absorbed by the whole structure is not exactly the algebraic sum of the energy absorbed by the tube and by the foam. A small amount of the energy has dissipated through the friction due to the interaction between the foam and the tube during the crush.

3.3 Parametrical study

Parametric study has been carried out to understand the influence of designable parameters on the energy absorption of the foam-filled tube, which would assist us to optimize the structure. Generally, the energy absorption of a foam-filled tube depends on the material properties of the tube and the foam, the geometry of the structure and the friction coefficient between the tube and the foam. The energy absorption also increases with the increase of the compressive displacement. All the parameters involved in the crushing simulations are listed in Table 1. Mathematically, the energy absorption is a function of all the parameters, *i.e.*,

$$E_A = f(E_t, \nu_t, \sigma_{Yt}, n, E_f, \nu_f, \alpha, Y, L, D, t, f, U) \tag{5}$$

Dimensional analysis is a powerful tool to parametrically study a complicated system, which involves many parameters.[15,16] According to the Buckingham Π-theorem for dimensional analysis we can reduce the number of parameters. For this problem we choose the Young's modulus E_t, and the diameter of the tube D as primary quantities. Therefore the dimensionless function for the energy absorption is:

$$\frac{E_A}{E_t \cdot D^3} = \Pi_1\left(\nu_t, \frac{\sigma_{Yt}}{E_t}, n, \frac{E_f}{E_t}, \nu_f, \alpha, \frac{Y}{E_t}, \frac{L}{D}, \frac{t}{D}, f, \frac{U}{D}\right) \tag{6}$$

In this study we focus on the influence of the geometric parameters, the friction and the displacement: L/D, t/D, f and U/D. The material properties are the same as in previous subsection.

The influence of the friction coefficient f on the normalized energy absorption E_A/E_tD^3 is shown in Fig. 9 with $L/D = 3$ and $t/D = 0.0375$. Only small change of normalized energy absorption is observed when the friction coefficient varies from 0.1 to 1.3. It indicates that the effect of the friction coefficient on the energy absorption is not significant. The reason is that the energy absorption due to friction is a small part of the total energy, which has been demonstrated in previous example.

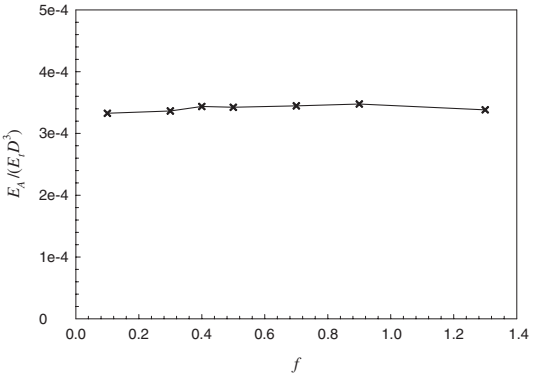

Fig. 9 Influence of friction coefficient on the the normalized energy absorption.

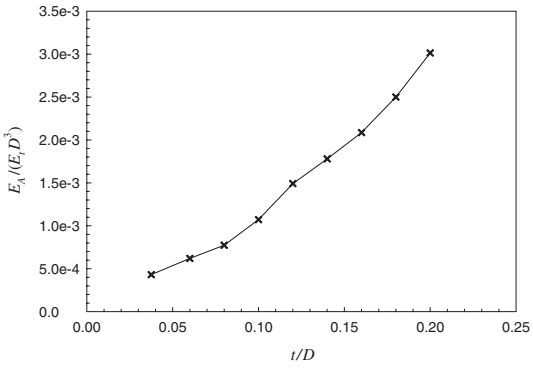

Fig. 11 Influence of the normalized tube thickness on the normalized energy absorbed.

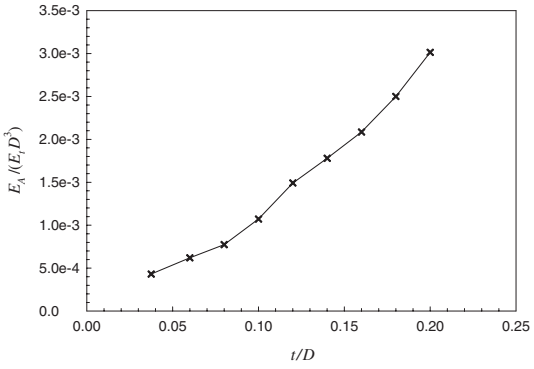

Fig. 10 Evolution of the normalized energy absorbed with the normalized compressive displacement.

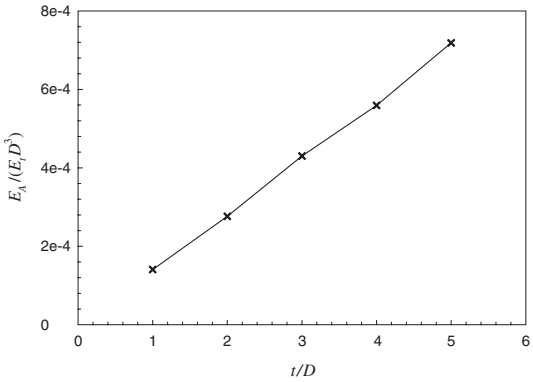

Fig. 12 Influence of the normalized tube length on the normalized energy absorbed.

It is interesting to study the evolution of the energy absorbed during a crush. Here it is the relationship between the normalized energy absorption E_A/E_tD^3 and the displacement of the upper rigid plate U/D. Figure 10 shows the result with $L/D = 3$, $t/D = 0.0375$ and $f = 0.7$. We can see that the normalized energy absorption increases quite linearly until the ratio U/D reaches 0.6. After that, the energy increases more rapidly. The explanation of this observation is that the foam is more compressed now and most of the pores have been squeezed out. At this moment the structure has a higher strength and can absorb more energy. When U/D reaches 0.8, no further crush is allowed and the simulation stopped.

The influence of the ratio t/D on the normalized energy absorption is shown in Fig. 11, where $L/D = 3$ and $f = 0.7$. The increase in the ratio t/D increases the normalized energy absorption E_A/E_tD^3. This result means that the energy absorption of the structure will increase if we increase the thickness of the tube while keeping the length and the diameter of the tube unchanged. This conclusion is intuitive because the aluminium tube takes more space than the foam in the structure when the ratio t/D increases. The aluminium tube has a higher strength than the foam and a higher capacity of absorbing energy. Nevertheless the increase in thickness also means the increase in the mass of the structure because the aluminium tube has a higher density than the foam. Similarly, we can find out that the energy absorption increases with the increase of the tube length, which is shown in Fig. 12 with $t/D = 0.0375$ and $f = 0.7$.

4. Conclusions

Numerical simulation of the crushing of foam-filled aluminium tubes has been carried out. It shows a fair agreement with experimental tests. The shapes of the post-buckling deformation are very similar to experimental observations. Our results clearly indicate that the energy absorption of a foam-filled tube is significantly higher than that of the tube without foam. Further parametrical study indicates that the energy absorption shows an improvement with the increase of the thickness or the length of the tube. Our results also indicate that the friction coefficient between the foam and the tube has negligible influence on the energy absorption.

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