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Numerical Partition of Energy Absorption of Foam-filled Top-Hat and Double-Hat Sections

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Abstract The interaction effect, i.e., the contribution of each component to the total energy absorption of an axially crushed foam-filled hat section was investigated quantitatively via numerical simulation. The FE results were first verified by experimental work of aluminum foam-filled top-hat and double-hat sections, then the contribution of foam-fillers and that of hat sections to the overall energy absorption were quantitatively obtained, respectively. When foam-filled, increase in energy absorption was found both in hat section component and foam-filler component, whereas the latter contributes predominantly to the interaction effect.

Key words: aluminum foam; top-hat; double-hat; energy absorption; finite element

INTRODUCTION

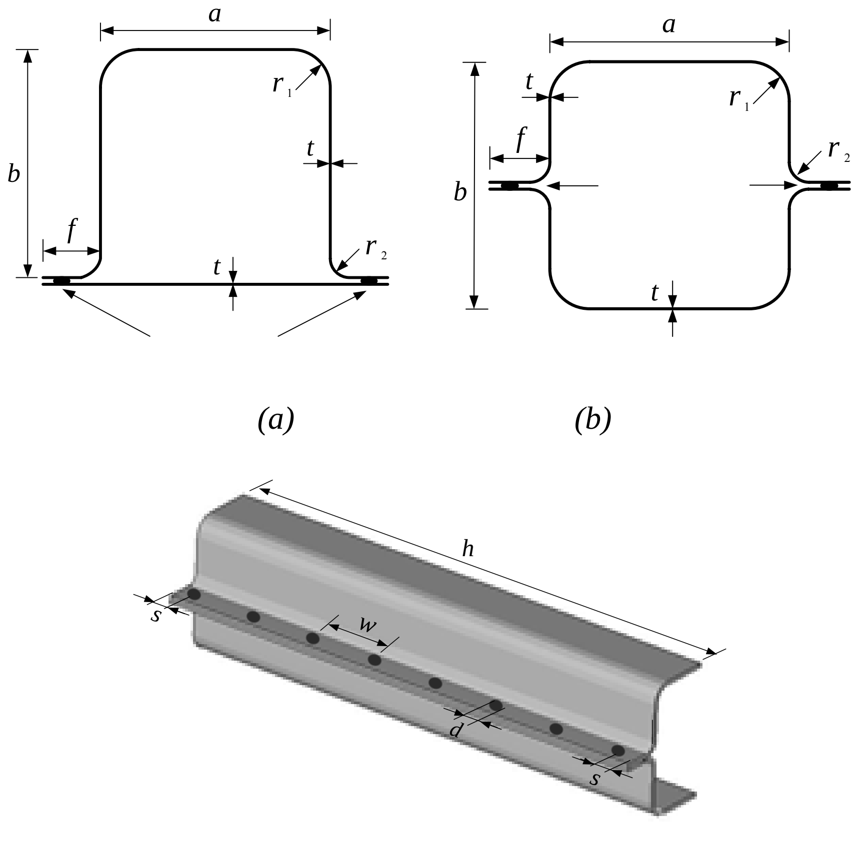
Recently, much attention is given to the foam material filled thin-walled structures[1-6]. The studies showed that the interaction between foam fillers and the supporting structures produce very excellent crushing behaviors and energy absorption characters. Hanssen et al.[1] summarized that the "interaction effect" principle in these compound structures: the increased number of lobes created by introducing foam filler causes the force level of the foam-filled columns to be significantly higher than that of the combined effect of non-filled column and foam alone. The interaction effect is favorable to the crashworthy application. However, up to now little work has been conducted to quantitatively determine this effect, i.e. the contribution of each component of the compound structure to the total energy absorption.

Santosa and Wierzbicki[2] developed a formula for the crushing force of foam-filled structures by using numerical simulation results. Hanssen et al[3] also suggested an empirical relationship in the similar form. Though quantitative work they are, no partition data were given.

In the present study, the mild steel hat sections were adopted while examining the interaction effect of foam-filled thin-walled structures. Hat sections are very popularly used in various vehicles, e.g., the front rail is a typical top-hat structure, and the door pillars are typical double-hat structures. These structures are the main crashworthy members dissipating impact energy during an accident event. Experiments showed that the mean crushing force of mild steel hat sections is several time higher than that of foam columns with similar geometry, and no spot-weld failure or rupture of the skin was found in the foam-filled hat sections, indicating a perfect matching-up of the filler and the supporting structure. The energy absorption of each components of the foam-filled hat was examined through FE simulation by software package LS-DYNA, and quantitative partition is reached. This analytical work is helpful to the crashworthy design of the foam-filled compound structures.

EXPERIMENTAL

1. specimens The geometry of top-hat and double-hat structures with spot-weld arrangement is shown in Fig.1. The corresponding size values are listed in Table 1.



(a) (b)

(c)

Fig.1 Specimen geometry and spot-weld characters (a)cross section of a top-hat specimen. (b) cross section of a double-hat specimen. (c) spot-weld arrangement

Table 1 Geometry of hat sections

Wall thickness $t\,(mm)$	$a\,(mm)$	$b\,(mm)$	Height $h\,(mm)$	Flange $f\,(mm)$	Inner rolling radius $r_1\,(mm)$	Outer rolling radius $r_2\,(mm)$	Spot-weld distance $w\,(mm)$	Edge distance $s\,(mm)$	Spot-weld diameter $d\,(mm)$
1.5	50	50	200	15	6	4	27	5.5	6

It is noted that each hat section is composed of two parts, therefore it has discontinuous walls. The top-hat comprises a hat with curved cross section and a closing plate; and the double-hat comprises two hats with curved cross section. The two parts were jointed by spot-weld, with the spot diameter of about $d = 6mm$. The aluminum foam samples, named PML-725, were provided by Luoyang Material Research Institute of China. They were produced with the melt route technique and in an average densitiy of ρ_3=0.37g/cm^3.

2. Basic collapse modes Hat sections show very good capability to adept to a stable crushing. When foam-filled, the structure shows an even better stability. For both top-hat and double-hat, the basic collapse mode of foam-filled structure and its corresponding hollow structure are shown in Fig.2, and they share the same collapse mode, except that there is a decrease in the folding length and increase in the number of lobes for the filled section. In Fig.2, the non-filled hat sections formed 3 lobes, while the foam-filled sections formed as many as 5 lobes, for both top-hat and double-hat.

(a) *(b)* *(c)* *(d)*

Fig. 2 Basic collapse modes: (a)non-filled top-hat, (b)foam-filled top-hat, (c)non-filled double-hat, (d)foam-filled double-hat

3. Interaction effect Fig.3 illustrated the interaction effect in the form of crushing force histories. Hanssen et al.[4] described the interaction effect as the following: the increased number of lobes created by introducing foam filler causes the force level of the foam-filled columns to be significantly higher than that of the combined effect of non-filled column and foam alone.

The experimental work on foam-filled hat sections in the present study also found the interaction effect. And not only the crushing force, but also the specific energy absorption of a foam-filled column shows the similar tendency.

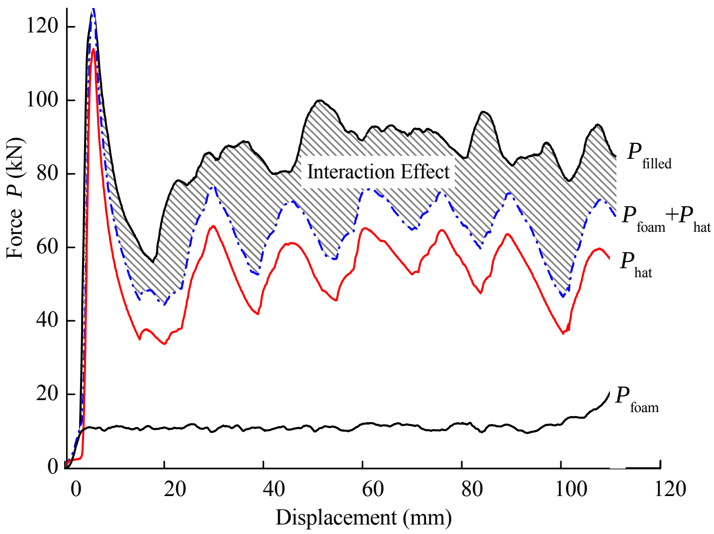


Fig.3 The interaction effect of foam-filled hat section

To sum up, the interaction effect can be expressed as

Or in the forms of crushing force and specific energy absorption

$$P_{filled} > P_{hat} + P_{foam}$$
$$E_{s,filled} > E_{s,hat} + E_{s,foam} \tag{1}$$

where P stands for crushing force, E_s stands for specific energy absorption, subscription "fill", "hat" and "foam" stands for the filled hat section, hollow hat section and free aluminum foam respectively.

It seems to be, however, an unconquerable task to quantitatively determine relative contribution of thin-walled structures and foam-fillers to the interaction effect merely from experiments. Numerical analysis are therefore adopted in the next steps.

FINITE ELEMENT MODELING

Nonlinear explicit finite element LS-DYNA package was employed to simulate the crushing characteristics of foam-filled hat section. Two steps were adopted in this analysis: first, the simulated force-displacement histories and simulated collapse mode were validated with those of experimental; second, the simulated crushing forces were partitioned into the contribution of the foam-fillers component, the supporting hat component and the foam-filled hat section, and the partitioned forces were compared with those of corresponding non-filled hat sections, unbounded foam columns, and the sum of the two individuals.

Several typical material model that may fit for aluminum foam were provided by LS-DYNA, they are honeycomb, closed cell foam, low density foam, crushable foam, Bilkhu/Dubois and improved honeycomb, with the material ID of #26,#53,#57,#63,#75 and #26 in LS-DYNA. The comparison of material #57 and #63 were listed in Fig.4. The crushing morphology and load character of crushable foam material #63 give the better result. The yield surface of a crushable foam is

$$f_i = |\sigma_i| - Y = 0 \tag{2}$$

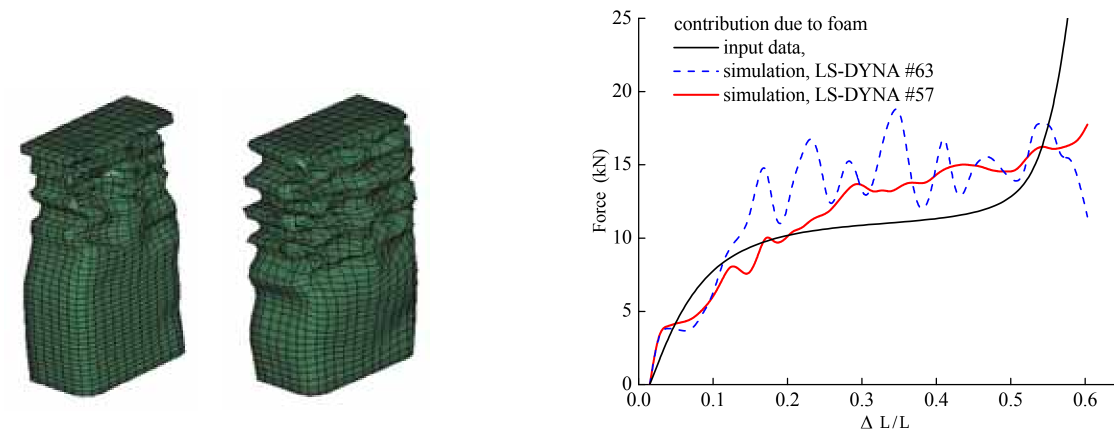
In the implementation the Young's modulus is constant and the stress is updated by assuming a elastic behavior

$$\sigma_{ij}^{trial} = \sigma_{ij}^{n} + E\dot{\varepsilon}_{ij}^{n+1/2}\Delta t^{n+1/2} \tag{3}$$

The magnitude of the principal value σ_i^{trial} $(i=1,3)$ are then check to see if the yield stress σ_y is exceeded and if so they are scaled back to the yield surface

$$\sigma_y < |\sigma_i^{trial}| \quad \text{then} \quad \sigma_i^{n+1} = \sigma_y \sigma_i^{trial} / |\sigma_i^{trial}| \tag{4}$$

Fig.4(b) gives the comparison of input shortening-force and output shortening-force of an aluminum foam-filler in different material model.



(a) *(b)*

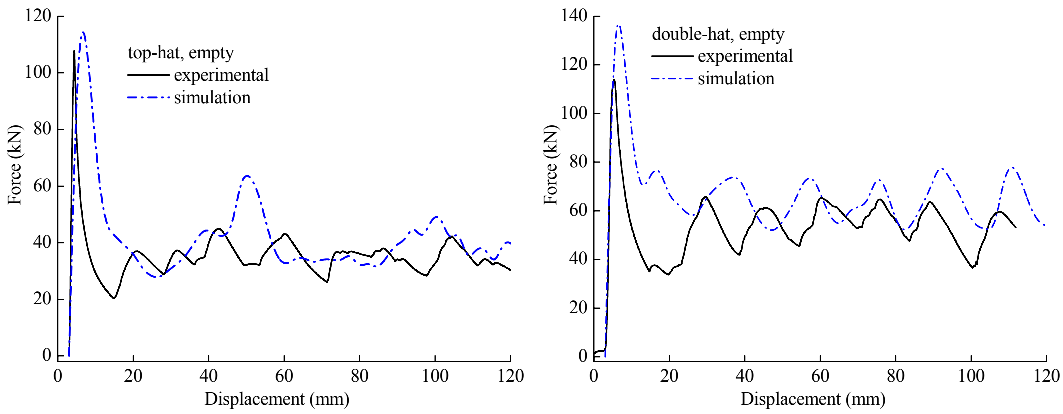
Fig.4 Comparison of material model #57 and #63. (a) crushed mode of foam fillers, left: low density foam #57; right: crushable foam #63. (b)the shortening-load curve of different model and input data

A successful FE simulation of the crushing behavior of a foam-filled hat section should be in accordance with experiment both in the collapse mode and the crushing history. Fig.5 gives a good validation of the simulated collapse modes.

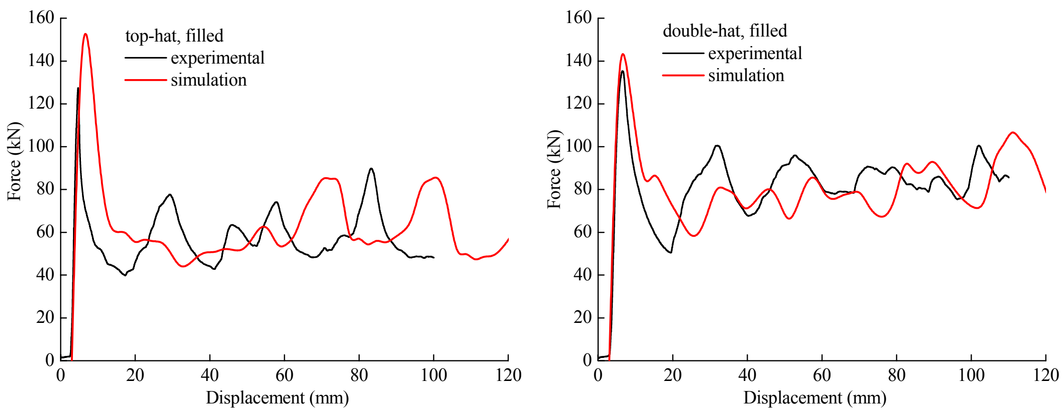
(a) (b)

Fig.5 Validation collapse modes of simulation with those of experiment: (a) empty hat section, with simulated in the left and experimental in the right; (b) foam filled hat section, with simulated in the left and experimental in the right.

The comparison of simulated crushing force histories with those of experimental also shows good results in non-filled top-hat, non-filled double-hat, foam-filled top-hat and foam-filled double-hat, as can be seen in Fig.6.



(a) *(b)*



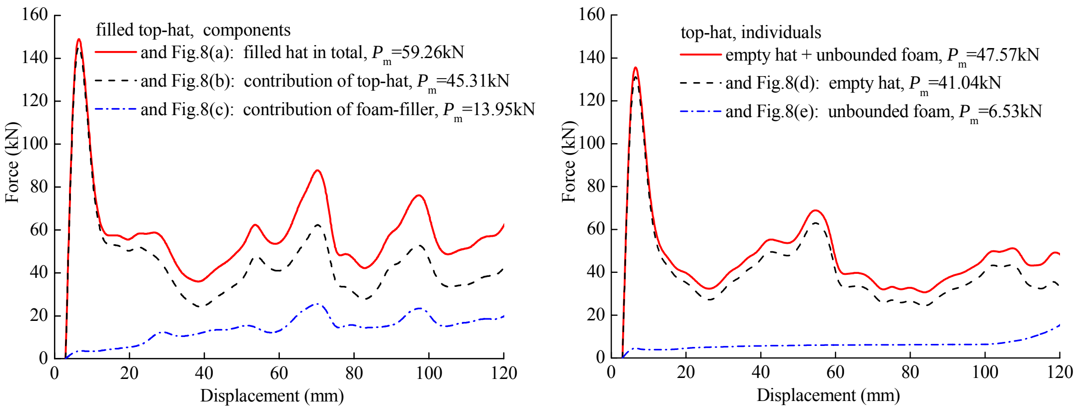
(c) *(d)*

Fig.6 Comparison of crushing force histories of simulation with those of experimental: (a) non-filled top-hat; (b) non-filled double-hat; (c)filled top-hat; (d)filled double-hat

PARTITION ENERGY ABSORPTION

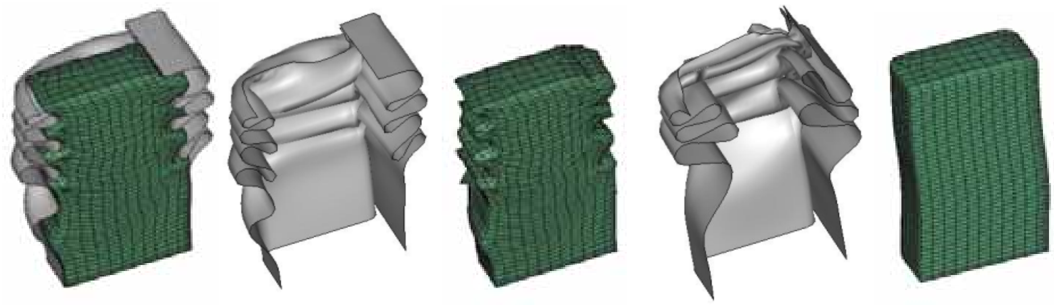
The advantage of FE simulation over experiment is that the mechanical information of any desired part can be effectively obtained when the model is properly designed. By defining the contact and part assembly relationships, the crushing histories of each component of a foam-filled structure, i.e., foam-filler component and supporting hat-component, are separated. Meanwhile, individual hollow hat sections and free (or unbounded) foam columns in the same size as those of foam-fillers are simulated under the same loading condition. The difference in mean crushing force of the foam-filled structure and the sum of individual hollow structure and the individual unbound foam column is a quantitative express of the so-called interaction effect. The interaction effect can be further measured through the contribution of foam-fillers and supporting hats, by comparing the component filler with unbounded foam column and comparing the component supporting hat with the hollow hat section.

Fig.7 to Fig. 10 gives the partition of both top-hat and double hat in the form of crushing history, mean crushing force and collapsed mode. And the contributions of each part to the interaction effect are listed in Table 2.



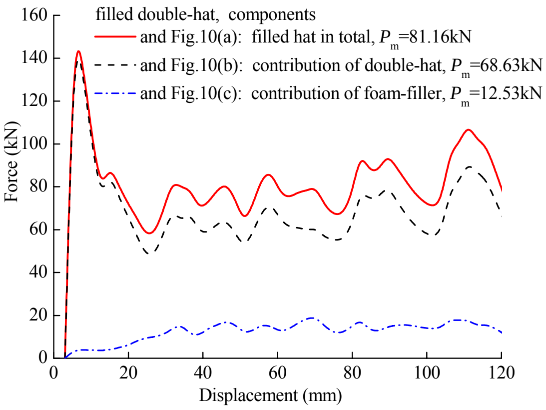
(a) *(b)*

Fig.7 Partition crushing force of simulated filled top-hat, and compared with corresponding simulated individuals. (a) foam-filed components; (b) corresponding individuals

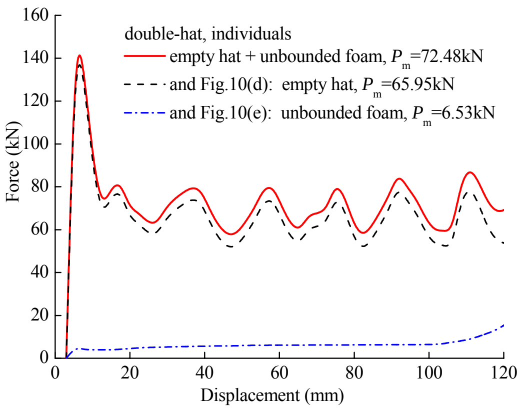


(a) *(b)* *(c)* *(d)* *(e)*

Fig.8 Interaction effect expressed in the form of simulated collapse mode, when these modes represent the mean crushing force or energy absorption, one gets $(a)=(b)+(c)$; $(a)>(d)+(e)$. *(a) filled top-hat; (b) top-hat component; (c) foam-filler component; (d) empty top-hat; (e) unbounded foam column.*

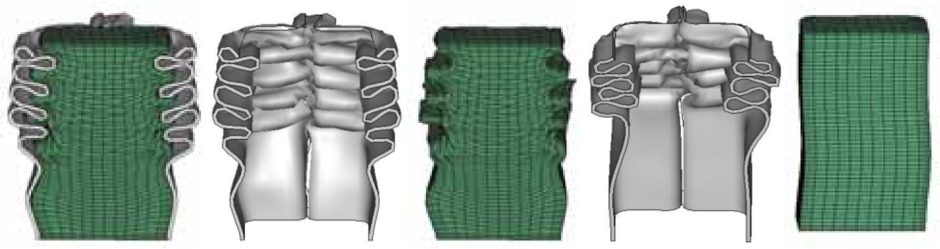


(a)



(b)

Fig.9 Partition crushing force of simulated filled double-hat, and compared with corresponding simulated individuals. (a) foam-filed components; (b) corresponding individuals



(a) (b) (c) (d) (e)

Fig. 10 Interaction effect expressed in the form of simulated collapse mode, when these modes represent the mean crushing force or energy absorption, one gets $(a)=(b)+(c)$ *;* $(a)>(d)+(e)$ *. (a) filled double-hat; (b) double-hat component; (c) foam-filler component; (d) empty double-hat; (e) unbounded foam column.*

Table 2 Partition interaction effect

Type		Hat section P_m (kN)	Foam column P_m (kN)	Total P_m (kN)
Top-hat	Filled-hat components	45.31	13.95	59.26
	Individuals	41.04	6.53	47.57
	Interaction effect	4.27(10.4%)	7.42(114%)	11.69(24.6%)
Double-hat	Filled-hat components	68.63	12.53	81.16
	Individuals	65.95	6.53	72.48
	Interaction effect	2.68(4.1%)	6(91.9%)	8.68(12.0%)

Both foam-filler and hat-section of the filled structure show higher mean crushing force than their individual counterparts. It is demonstrated that the increase in energy absorption of the crushed foam-fillers compared to the free foam columns accounts for the main contribution to the interaction effect (with 114% and 91.9% increase in filled top-hat and double-hat, respectively). But due to the lower crushing strength of the foam, the total interaction effect is about 24.6% and 12.0% increase in the mean crushing force, for top-hat and double hat structures, respectively.
If the collapse modes in Fig.8 and Fig.10 stand for the mean crushing force or energy absorption of corresponding components and individuals, according to the results from Table 2 and also from Fig.7 and Fig.9, there exist

$$(a) = (b) + (c)\ ;\ (b) > (d)\ ;\ (c) > (e)\ ;\ \text{and}\ (a) > (d) + (e) \tag{5}$$

CONCLUSIONS

When a hat-section is filled with aluminum foam, increase in energy absorption was found both in hat section component and foam-filler component, whereas the latter contributes predominantly to the interaction effect. This analytical work is instructive to understand the energy absorption mechanism of foam-filled structures. However, further investigation may be carried out in the experimental category to examine some details and predictions of current work.

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