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FINITE ELEMENT SIMULATION OF POLYMETHYL-ACRYLAMID FOAM-FILLED ALUMINUM 2024-T4 TUBE UNDER DYNAMIC AXIAL LOADING

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Abstract
This paper presents the numerical studies of two different tubes under axial impact loading structures. The cylindrical tubes are filled with closed-cell polymeric foam. The deformation and failure mechanisms of this material were observed and analyzed numerically using the finite element method. The varied wall thickness and dynamic velocity of impact were examined throughout this paper. In comparison with double cell foam-filled tubes in terms of dynamic loading, mean load and absorbed energy were enhanced, and the weight efficiency of energy absorption is higher. Parameters affecting the performance of the foam-filled tube structures are also studied. The used of polymeric foam as a filler material is superior compared to empty tube thin-walled profile when polymeric foam filled into tubular structure. Finite element software package of ABAQUS version 6.10 was used to analyze the performance of absorbed energy as well as dynamic and mean load characteristics. The polymethyl-acrylamid foam was selected as a filler material and thin-walled metallic material of aluminum 2024-T4 alloy.

Keywords: Thin-Walled Structure, Finite Element Modeling, Progressive Damage, Foam-Filled,ABAQUS/Explicit

1. Introduction

During the past two decades, many research study works have been done to study the axial crushing behavior of thin-walled columns, which work as energy absorption performance, in order to improve their capability of absorbed energy of material structure. As the results obtained in many related works, empty tubes are lower than crushing load in term of absorbed energy due to their empty space of hollow section. In order to achieve higher absorbed energy in term of dynamic loading condition regime the crucial factor in this factor to create something new of using the foam as filler material filled into the tubular hollow section. From the previous study on energy absorption of structure, the weight efficiency in energy absorption was to take consideration because the structure of crashworthiness should be less than weight for lower value of inertia characteristics. The crushing behavior of such structures was studied by many researchers in the past several years. Santosa and Wierzbicki and Santosa et al. investigated the effect of foam filling on the resistance of thin-walled square columns through numerical simulation and quasi-static experiments. It was shown that filling of foam improved the load-carrying capacity by offering additional support from inside and increases the energy absorption. It was also pointed out that partial filling of foams increased the energy absorption to weight ratio of the structure. The three-point bending behavior of the foam-filled cylindrical tubes was studied by Xie et al. They showed that higher foam density could increase the load-carrying capacity of the foam-filled cylindrical tube but will reduce the displacement before failure. The bending behavior of hat profiles filled with aluminum foams was studied by Chen. It was found that filling of aluminum foams increased the specific energy absorption of the structures. Chen et al. performed numerical simulation and weight optimization on foam-filled sections under bending condition. The results showed the potential of thin-walled columns filled with aluminum foams as weight-efficient energy absorbers. Zarei and Kröger studied the bending crash behavior of empty and foam-filled thin-walled square aluminum beams experimentally and numerically. An optimization procedure was applied to find the optimum foam-filled beam that absorbs the same energy as optimum empty tubes with lower weight. Kim et al. studied the bending collapse of thin-walled cylindrical tubes filled with several pieces of foams experimentally and numerically. They pointed out that the bending resistance of tubes with three pieces of filler was higher than that with one piece of filler. For a structure under bending, the energy absorption as well as the bending resistance is of importance when considering its crashworthiness. Although filling of aluminum foams increases the bending resistance of thin-walled columns, it is found that columns filled with aluminum foams fail much earlier than those without fillers, which limits the energy absorption of the structures. The deformation and failure mechanism are analyzed, and the results are compared with those of foam-filled two type's arrangement filler materials. The objective in this study were to develop finite element model of double cell tube filled with polymeric foam in arrangement of cell in tube inner structure. The commercial software of ABAQUS/ Explicit version 10.0 was used to carry out the crushing behavior of double cell tube under axial dynamic loading.

1.1 Finite Element Model

It is well known that numerical simulation using finite element analysis allows wide variety of enhancement. Therefore, ABAQUS/EXPLICIT version 6.10 was used throughout the analysis. The simulation processes have two differences composition of tubes, which are type A double cell with centered one cell in center thin-walled tube, and secondly the cell was 45 degree cross-section with bottom left side and upper right side view from top sides. Shell elements are used to model structures in which five integration points were selected for each simulation analysis. The two difference wall-thickness was analyzed significantly, and the stresses in the thickness direction are negligible. Generally three-dimensional shell elements are available with three different formulations; general-purpose, thin only and thick only. General-purpose shell elements are valid for use with both thick and thin shell problems. Furthermore, all general-purpose shell elements consider finite membrane strains. All special-purpose shell elements assume finite rotations; however, they assume small strains.

1.2 Crushing Parameters and Material Properties

The initial velocity (*V*) of the tube is set to be 6 m/s, hence calculated value for crushing time; (t) was found to be 0.02 s. The other important parameter of representing crushing event is boundary condition. In structural analyses, boundary conditions are applied to those regions of the model where there displacements or rotations are known. Such regions may be constrained to remain fixed or may have specified nonzero displacements or rotations. In this model the ENCASTRE ($V1 = V2 = V3 = VR1 = VR2 = VR3 = 0$) condition has been used where the top section of the tube is constrained completely and thus, cannot move in any direction also. The bottom section, however, is fixed in the horizontal direction but is free to move in vertical direction ($V1 = V2 = VR1 = VR2 = VR3 = 0$). The direction in which motion is possible is called degree of freedom (dof), hence this model only has a single degree of freedom. A mechanical, concentrated force with a magnitude of 500 N was applied in order to initiate the crushing process. The actual load magnitude is not critical because ABAQUS will report buckling loads as a fraction of the applied load.

Two types of models were analyzed in this study. Square models were arranged as tubular ones, material of Aluminum 2024-T4 Alloy was used to determine the crushing behavior and having of 60 x 60 mm and 1.0, and 2.0 mm wall-thickness. The double cell models were carried out from two tubes having outer wall from the same material wall of tube. All sections had a length of 150 mm. The sections were tested as filled with the polymethyl-acrylamid foam, while double cell. Table 1 illustrates typical test model geometry, whereas. Figure 2 presents' tensile stress-strain data curves of the used materials. In this study the velocity dynamic of impact was applied at 10 and 20 m/s axially onto the frontal crash flat plate analytical rigid surface.

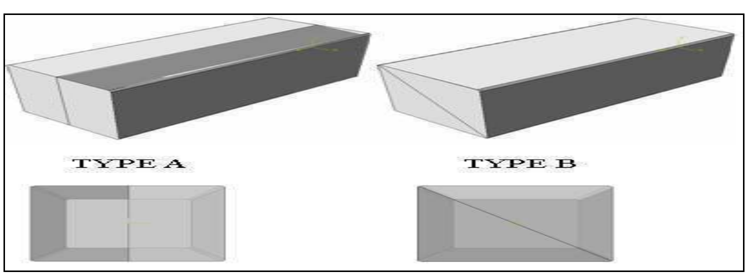


Figure 1: Test model geometry of type A, B and C

Table 1: Dimension of column finite element modeling

Type (tube)	*Length (mm)*	*Width (outer) (mm)*	*Velocity (m/s)*	Polymethyl-acrylamid Foam Density	*Thickness (mm)*
A	150	60 x 60	10, 20, 30	100	1.0, 2.0
B	150	60 x 60	10, 20, 30	100	1.0, 2.0

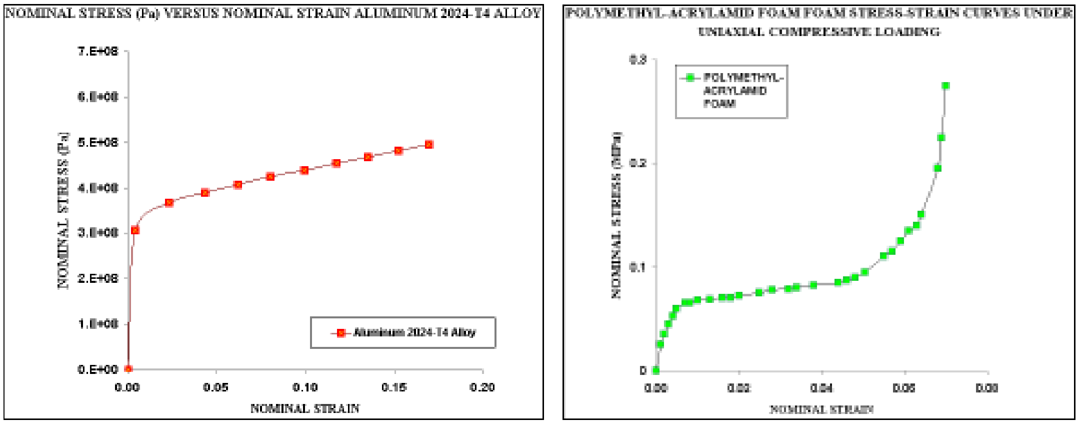


Figure 2: Nominal stress-strain curve of material aluminum 2024-T4 alloy and polymethyl-acrylamid foam

2. Crushing Process

The simulation, which normally is run as a background process, is a stage in which ABAQUS/Explicit solves the numerical problem defined in the model. ABAQUS/Explicit is a special-purpose analysis product that uses an explicit dynamic finite element formulation. It is suitable for short, transient dynamic events, such as impact and blast problems, and is also very efficient for highly nonlinear problems involving changing contact conditions, such as forming simulation. It is well known that a nonlinear structural problem is one in which the structure's stiffness changes as it deforms. All physical structures are nonlinear. In this simulation the stiffness is fully dependent on the displacement; the initial flexibility can no longer be multiplied by the applied load to calculate the spring's displacement for any load. Results evaluation can be done once the simulation has been completed and the reaction forces, displacements, energy or other fundamental variables have been calculated. The evaluation is generally done interactively using the visualization module of ABAQUS/CAE.
The visualization module, which reads the neutral binary output database file, has a variety of options for displaying the results, including color contour plots, animations, deformed shaped plots, and X–Y plots. The total work done (W) during the axial crushing of the cones are equal to the area under the load/displacement curve and is evaluated as:

$$W = \int P ds \tag{1}$$

where, P is the force acting on the tube. Therefore the specific energy absorption per unit mass, E is recognized as:

$$E = \frac{W}{m} \qquad 2)$$

where, m is the crushed mass of the thin-walled tube.

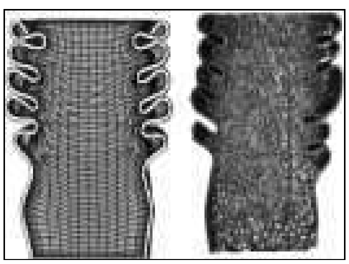
It was assumed that thin-walled aluminum extrusion has only isotropic strain hardening, and for quasi-static loading, the strain rate effects on the yield strength were neglected due to the relatively low overall average load rate used in the tensile tests. For dynamic loading, the effect of strain rate was included in the finite element model using the Cowper–Symonds constitutive equation given by the following relation:

$$\dot{\varepsilon}_p = D^t\left(\frac{\sigma_d}{\sigma_s}-1\right)^{q^t} for \mapsto \sigma_d \geq \sigma_s \tag{3}$$

where σ_d is the dynamic flow stress at a uniaxial plastic strain rate ε_p, σ_s, the associated static flow stress, and the constants D^t and q^t are tube material parameters. Equation (3) is an overstress power law that was incorporated into the finite element model.

2.1 Validation Of The Finite Element Model

Numerical simulation using finite element codes is currently an important approach to learn in the crushing behaviors of foam-filled columns. Santosa et al. (2000), Hanssen et al. (2002) and Reyes et al. (2004). The interaction effect of foam-filled hat section. H.-W. Song et al. / International Journal of Solids and Structures 42 (2005) 2575–2600 2581 name some of the most recent work, used explicit dynamic finite element codes like LS-DYNA and PAM CRASH to perform this kind of simulation. Some key issues in the modeling, such as material model for aluminum foam, contact definition; friction effect, boundary condition and the bridge from dynamic to quasi-static were discussed. In this work, nonlinear finite element ABAQUS/Explicit version 6.10 package was employed to simulate the crushing characteristics of foam-filled section. The foam filler was modeled with 8-node solid element. The model is highly dependent upon the mesh quality and mesh size, due to the conditional stability characteristic for an explicit finite element code. Shell elements and solid elements were modeled in a character size of 3 mm and 5 mm, respectively. The difficulty is how to model the polyurethane foam. Hanssen et al. (2002) gave an exhaustive study on validation of different available foam models in LS-DYNA, and concluded that none of the models managed to represent all load configurations with convincing accuracy. Therefore, one must prepared to neglect some trivial details and focus on the fundamentals while modeling. After careful validation, material model 63 for example, crushable foam material in LS-DYNA (Hallquist, 1998) was selected to model the aluminum foam in the present study. The model assumes a constant Young modulus, and the stress is updated by assuming an elastic behavior in the implementation. Strain–stress curve of the foam obtained from the uniaxial compression experiment was input into the model. Since the aluminum foam filler would undergo extremely high local compression and distortion, internal contact algorithm must be applied to the solid elements to prevent negative volume and numerical collapse. Rigid body property was assigned to the shell elements, because no fracture or failure or deformation was observed in the spot-weld in the experiments. Only half of the specimen was modeled due to the symmetry character. The load was applied at the upper end of the specimen with a constant displacement condition, through a rigid body which is modeled with shell elements. Validation and verification of the finite element model is necessary before an effective partition work could be carried out.



Parameters	Experimental	Numerical	Error (%)
Total compression (mm)	150	168	10
Peak load (kN)	85	96	11.4
Mean load (kN)	65	50	23
Absorbed energy (kJ)	21	19	9

Figure 3: Verification of collapse modes foam filled section, with the simulated on the left and experimental on the right and percentage error experimental and numerical analysis results as well as data result for comparison with an error both of them.

3. Result and Discussion

With respect to the failure modes of test series polymethyl-acrylamid foam filled square extruded aluminum 2024-T4 alloy profiles with small cross-sectional dimensions the numerical revealed that progressive buckling could almost exclusively be observed for some empty tubes and the foam filled crush elements with square cross-sections in Figure 4. All square double cell profiles of this analysis test series having a foam density than the square ones rather showed local progressive damage, but not typically progressive, deformation behavior, where the formation of folds began at different locations, generally not in a sequential manner. Furthermore, these element models buckled extensionally with all folds moving outwards, which is obviously caused by the presence of the foam core. The extensional deformations are also evident from the dynamic load compression displacement curves in Figure 4, because the load fluctuations are much more pronounced. Filling polymethyl-acrylamid foam inside of the tubes was in general accompanied by shorter wavelengths of the individual folds which is holds true for all element model test series. Within element model test series double cell square tubes, which were arranged in different ways, double cell, and arrangement with dimension of inner square tube profile, were analyzed.

Regarding the mean load efficiency, distinct enhancements due to foam filling are shown in Figure 4 for all investigated crush elements. The filled tubes of element model test series deliver improvements of up to 40 ± 50% for all cross-sectional shapes. Even higher absolute values for double cell can be observed for the corresponding crush elements model, mainly owing to the higher mean force efficiencies of the inner with respect to the combination of tube and foam to build up mass efficient energy absorption devices it has to be taken into account that the mean load efficiencies of the constituents should not differ much. The lower mean load efficiency for the tubular member will be advantageous. The filling foam density leads to:

(1) An increased tendency for the outer tubes to buckle extensionally,
(2) An increased tendency towards global failure,
(3) But also to the activation of higher interaction effect

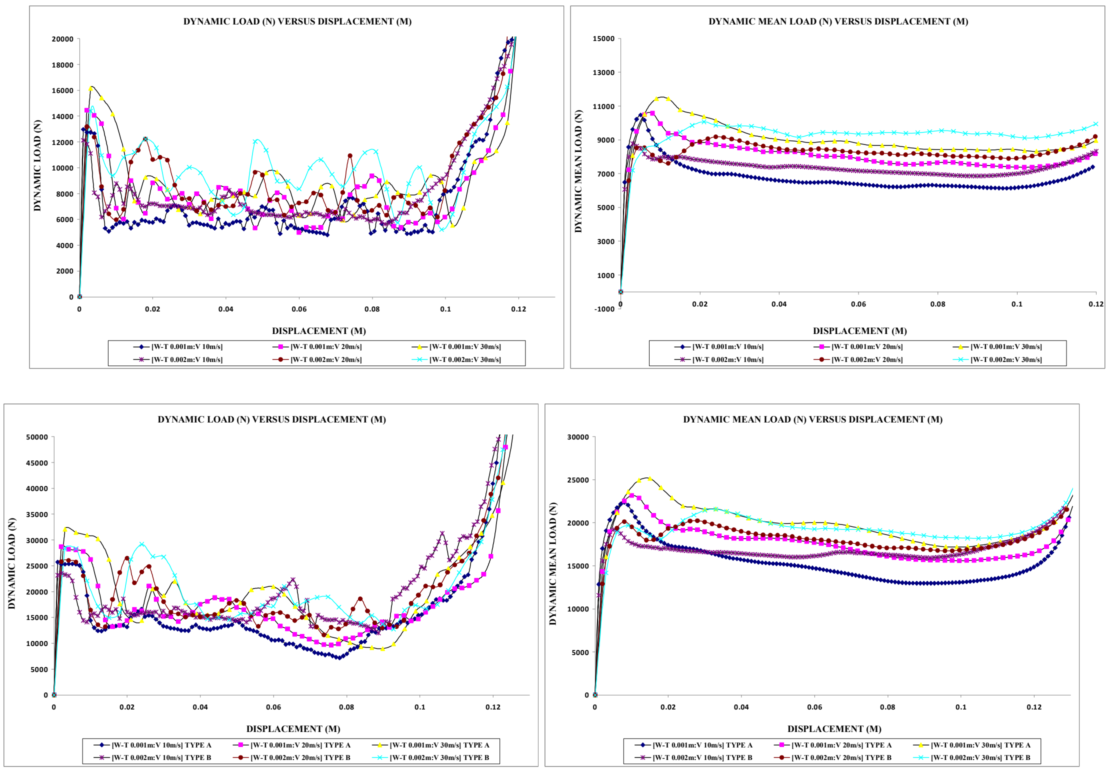


Figure 4: Dynamic and mean load (N) versus displacement (m) type of A and B tube profile (Wall-Thickness = 1.0, 1.5 and 2.0 mm: Velocity = 10 and 20 m/s)

The results obtained for the different efficiency parameters, which is showed in Figure 4, are presented for all 2 different types of element model test series in dynamic mean load versus displacement curve form in Figure 4. For the empty square filled profile double cell of element model test series where an increasing the wall-thickness of square inner and outer profile the dynamic mean load will increase opposite of displacement curves. The axial compression load capacities were crushed progressively when square profile increases a thickness. The reduction of the stroke efficiencies can certainly be traced back to the foam behavior. With filled with foam into the region of densification, where the compressive dynamic load starts to increase steeply and shifted to lower values of the compressive strain. The typical progressive buckling characteristics, which could be observed in most numerical analysis of this test series of wall thickness 1 and 2 mm as well as variable dynamic impact loading of 10 and 20 m/s are evident from the deformed elements shown in Figure 5. The type of A, and B cell square profile also reveals the higher densification in the outer region of the foam core due to a multiaxial state of compression illustrated resulting from foundation effects of the foam with respect to the profile. Global failure was observed only for the double cell foam filled elements.

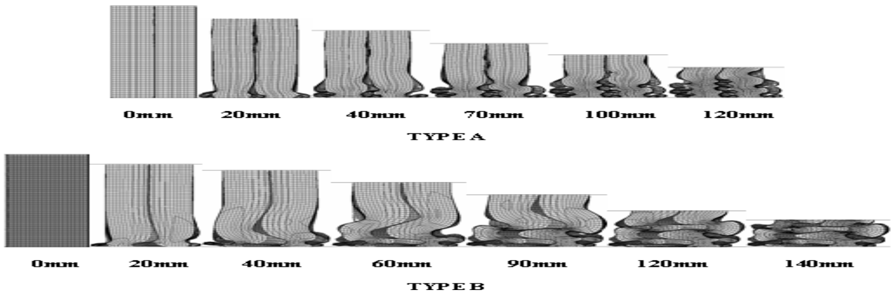


Figure 5: Deformation pattern of type of A and B tube profile (Wall-Thickness = 1.0 mm: Velocity = 10 m/s)

This can be traced back to global buckling of the slender inner profiles, leading to overall buckling of the whole arrangements. All filled element modeling that deformed locally began to buckle in an extensional mode, but after the formation of some folds most switched to an inextensional mode, which is typical for the empty profiles of this type of A, B and C. The measured dynamic loads versus displacement curves from Figure 5 also clearly display the effects of the change of deformation modes. The double cell element model show a pronounced load fluctuation during the load cycles, owing to the extensional folding modes, which is followed by minor differences between maximum and minimum loads due to the inextensional buckling deformations of the extruded aluminum 2024-T4 alloy tubes.

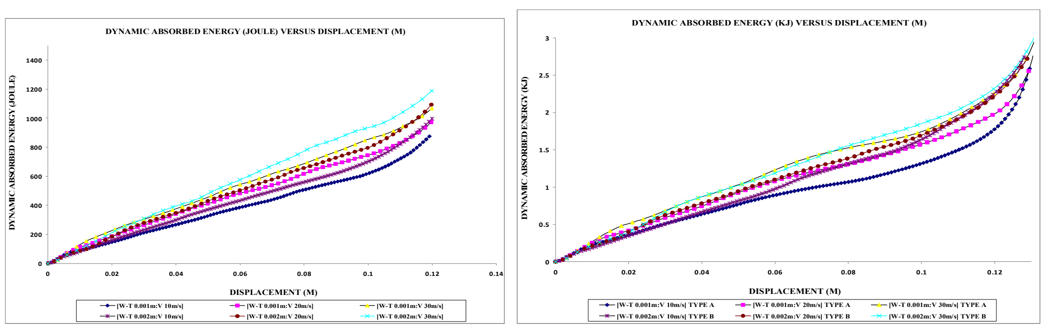


Figure 6: Dynamic absorbed energy (Joule) versus displacement (m) type of A and B profile (Wall-Thickness = 1.0, 1.5 and 2.0 mm: Velocity = 10 and 20 m/s)

Furthermore, the dynamic load versus displacement curves reveal a distinct quasi-steady progress of the crushing forces which is fluctuating around a more or less constant value, provided that the average foam density is not too high. The stress - strain curves of uniaxially compressed foam cores shown in Figure 4, indicate that for foams of largest volume and maintain low densities no marked plateau region can be characterized by more or less constant stresses, but rather a region of constantly increasing stresses can be observed thus corresponding with the measured dynamic load versus displacement compression behavior of crush elements model filled with foams of higher volumes. Furthermore, many of the investigated elements started with the simultaneous formation of folds at different locations, and as a result a local, but not typically progressive buckling behavior could be observed. For the first stage this led in combination with breaking of the global buckling of the tubes. The gluing between filler and tubes of element model obviously caused the lobes to be filled with polymethyl-acrylamid foam for the most part almost of wall-thickness 1 and 2 mm square tube. However, some breaking of the interface can also be observed for these element models. It should be noted, however, that the main reason for applying fiction coefficient for these interaction surface of inner, outer and foam element geometries model. As a result, from Figure 10, the element model analysis apparent foam density of 100 kg/m^3, a regular progressive buckling behavior, dominated by inextensional folding modes and, hence, with not too large energy fluctuations, while retaining marked efficiency improvements with respect to the mean load. Because the stroke efficiency should also remain high for such densities, distinct improvements of the whole energy absorption capacity can be expected. To our experience this does not only apply to crush elements with square cross-section although the improvements are most pronounced in this case of double cell profile. Such metallic structures are, therefore, expected to be of advantage mainly in structures that have to resist considerable compressive load, so that larger cross- sectional dimensions have to be applied in any case.

4. Summary and Conclusions

The test element results model presented here confirm that the mass related mean load level may considerably be improved by filling tubular members with polymethyl-acrylamid foam. Provided that the plastic buckling behavior remains characterized by local modes, essential enhancements were obtained for all investigated shapes and dimensions. These improvements may partly be traced back to the axial compression of the foam cores themselves, but interaction efficiency is also play a substantial role that the simple estimates.

With respect to the total energy absorption capacity of a given crush element, however, improvements are less pronounced. The reason for this is that the maximal crushing distances, which may be utilized for energy dissipation, reduce with increasing foam densities. Nevertheless, improvements of the mass the investigation of double cell arrangements revealed that these may be preferable to analysis. It could be shown that improvements are mainly due to the presence of the inner profiles, which are in general more mass efficient than the outer ones. Interaction effects are somewhat less pronounced that for tubes. An analysis of interaction effects was performed, which not only allowed to determine the relative c influences of such effects onto the mean load levels but also to and some explanations concerning the differences between cross-sectional shapes and mono-and double cell arrangements, respectively. Furthermore, some basic conditions for the appropriate choice of tube filler combinations could be obtained this way. Design considerations, pointing out the essential constraints for the appropriate choice of foam densities for the construction of mass efficient crush elements, have been summarized. However, all considerations stated therein are restricted to the behavior of dynamically loaded crush elements, which are filled with polymethyl-acrylamid foam. Furthermore, influences of gluing have to be investigated in more detail, because they are expected to markedly influence the energy absorption capacity of filled crush elements. With respect to the design of `optimally tuned' composite crush elements, numerical methods could also turn to account, which allow to gain more insight into the mechanics of such complex plastic deformation processes.

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