Modeling Aluminum Honeycomb Under High Velocity Impact

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1 Introduction

Aluminum Honeycombs are classified as advanced engineering solution for specific requirements and utilized as composite core material, thermal isolator, optical aligner, floor mat, packaging filler and energy absorber for different industries. Many materials may be mentioned here as cheaper and simpler alternative that can offer similar or maybe higher performance for these purposes even with lower cost, however none of them can come close to the weight advantage of honeycombs thanks to the extensive air space and load path provided by its peculiar shape [1]. In conformity with our needs, this study takes its dynamic behavior under impulsive loads as focal point of which is maintained by buckling of ductile Aluminum sheets extensively without losing its integrity [2]. Such behavior has been exploited by many industries, especially ones deal with impacts such as automotive, defense and aerospace that a source of momentum is needed to be suppressed in a way that amplitude of force applied shall be reduced by extending the time of contact along with conversion of energy into internal energy induced by plastic deformation [3]. Quantity of kinetic energy absorbed per unit area by mentioned mechanisms is directly influenced by geometrical properties of honeycombs such as cell size, foil thickness and height of the layer. These parameters also determine the density of the honeycomb, and therefore require a trade-off considering the purpose. For low velocity impacts scenarios with wider contact surface, larger cell size is preferred to reduce weight and material cost [4,5], while intermediate/high velocity impacts require smaller cells as the incident is relatively local and higher kinetic energy is handled. Relation between the energy absorption and cell dimension can be described as the smaller the cell dimension, the more local collapse occurs and the higher mode of buckling is observed. This means amount of material contribute to plastic deformation is higher [6,7]. Material of the honeycomb is another design aspect to be considered and generally converges into several mechanical attributes like strength, ductility and density. When the system design allows larger volume of honeycomb to be employed on wide surface, composites (GFRP, aramid, etc.) can be matter of discussion as they ensure lightweight solution especially for aerospace products. These materials store significant amount of energy by complex damage mechanism and excessive friction of high strength fibers. Incident elastic peak load prior to the failure is limited due to ease of transition that occupant safety application often refers composite honeycombs [8,9]. Metallic honeycombs are heavier alternative for specific use but offer much higher energy dissipation by means of plastic deformation coupled with debonding cohesive layers between foils. Thus, composite materials cannot replace metallic honeycombs when the high amount of kinetic energy is to be absorbed within relatively lower thickness. Aluminum, in particular, bring in remarkable energy conversion performance over weight ratio by its characteristic ductility and low density. This is why many defense and aerospace industry products contain Aluminum honeycombs for protection against secondary ballistic particles or collateral impulsive loads. Under impulsive loads, mentioned ductility maintain collapse of foils onto each other simply by 180° folding without any mode I and mode II fracture [10-13]. The higher ductility the thicker foil can be fold without failure and the more material contribute on plastic deformation within a cell. Even though it is relatively expensive, 5xxx series of Aluminum is therefore preferred for aerospace products and ballistic protection systems since it has outstanding deformability along with satisfactory strength to maximize energy per unit volume.

Fig.1: Honeycomb after high velocity plate impact

Structural modeling of Aluminum honeycombs with numerical analysis methods is a live topic in which many improvements and new tools have been developed in last two decades. Seeking lightweight solution in terms of grams, not kilograms or tones, for more severe loads and harsher treats require advanced heterogeneous materials replace conventional products. Additional cost brought by this shift led designers to care for predictive studies by means of computer aided engineering tools to asses and tune their designs. Because of wide material model implementation and wide range of use documented in literature, LS-Dyna is the primary choice for modeling such materials subjected to dynamic loads extreme deformations. For occupant safety and crashworthiness studies, numerous papers have been published regarding modeling of honeycombs used in surrogate barriers and bumper design. Referring all of them here is not practical, but some of them shall be mentioned since their focus intersect with topic of this study. Simulation of automotive crash require modeling Offset Deformable Barriers (ODBs) and Movable Deformable Barriers (MDBs) which mechanically represent second vehicle with verified accuracy [14,15]. Finite element modeling of honeycombs in these barriers generally has two approaches that either solid continuum elements were chosen or directly modeled in so-called “meso scale” with shell elements. Solid elements with varying formulations require special anisotropic material models and some solution issues induced by element distortion [16-18]. As a straight-forward approach, models with shell elements use constitutive relation of aluminum alloy which may not require special characterization process, however bring significant CPU cost as collapse and folding mechanism shall be solved directly by smaller elements in order to reach desired accuracy [4, 19-21]. Mesh free methods have also been employed in several studies for low velocity automotive collision simulations. In The Geroge Washington University [22] accelerations were compared between experimental measurements and numerical analysis results whose honeycombs were solved with conventional finite elements, Element Free Galerkin (EFG), Arbitrary Lagrangian Eulerian (ALE). Results showed numerical outputs were very closed to each other and remarkably fits with experimental results measured by accelerometers. However, there was distinct solution cost of which EFG took almost twice as much as lagrangian discretization and even had higher CPU time then the one with full integrated element. It should be noted that, this study was held in 2005 in which solver technologies for mesh free methods were not mature and many implementations have been developed since then. In addition to that, very low collision speed (25mps) was investigated that element distortion induced time step variation and negative volume were not the factors determining solution time of finite element models. In fact, other study [23] reported comparison of CPU costs showed that efficiency of EFG solver became significant when severity of deformation increases as it provided more stable run and run time was not affected by element distortion as one with finite elements.

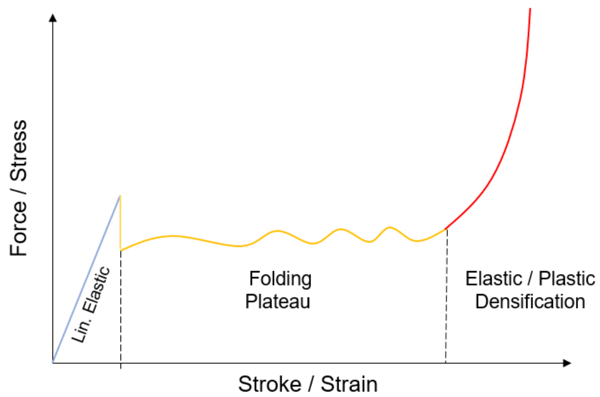

Fig.2: Mechanical behavior of ordinary Aluminum Honeycomb under compression

Increase in impact velocity gradually lead ratio of volumetric compression and locality of the deformation. To handle such kinetic energy with limited contact surface, smaller cell size is required as mentioned. Many aerospace studies have been published for medium to high velocity impacts and blast loading in which shell elements employed to evade issues related with element distortion and characterization. For hypervelocity impacts, kinetic energy sources were appeared as either single ballistic projectile or cloud of debris that all of them acted on small surface which allowed analyst to model small section of system. Shell elements with sub-millimeter edge length can therefore be used in discretization and consequently yield satisfactory accuracy. For space-debris impact studies, the channeling effect maintained by aluminum foils were also important focus of these studies where debris (modeled with SPH nodes) interact with inner surface of aluminum and spatially converge into impact axis, instead of spreading after penetration. In order to observe it and assess efficiency, foils were modeled explicitly with voids between [24-26]. In modeling studies for protection systems against blast type loading, area of the surface subjected to out-of-plane impulse are generally larger, however depending on the distance and type of the blast source, homogeneity of loads allows small section of the honeycomb can be modelled with all geometrical details and small shell element size. For example in ISL [24] modeling inputs such as section dimensions, mesh size, friction coefficients and rate sensitivity were discussed and compared with experimental results. It has been reported that after convergence study, 9 cells would be sufficient to represent homogeneous collapse with element size 0f 0.2mm. Surprisingly, friction coefficient was reportedly uninfluential and strain rate effect become significant when C parameter of Johnson-Cook model reach 10^{-1}. Considering the C parameter of Aluminum alloys which are generally vary at the order of magnitude of -3, measurement of exact value is not necessary for such purpose. In the study of University of Nevada [25], Belytschko-Tsay shells elements (ELFORM=2) with 0.24mm edge length were utilized in Aluminum foil discretization and blast load, which led complete collapse of honeycomb, was applied. When compared with experimental findings, though no rate dependency was included (`*MAT_PLASTIC_KINEMATIC`), good agreement was reported which supports insignificance of rate effects pro and verify sufficient element size / cell height ratio given in [24].

2 Simulation Case

All studies above gave good perspectives for modeling process of Aluminum honeycomb which has been used in ballistic protection systems as kinetic energy absorber. At the beginning direct modeling approach had been adopted with shell elements using mentioned discretization method according to foil thickness cell size. However, because honeycomb was employed in many locations for different purposes, impractical simulation time induced by low times steps and extreme DOF count was observed. Seek for an alternative method was inevitable that required significant characterization and verification process.

Because of the strict confidentiality and commercial concerns, exact function of the material, dimensions, velocities, and material model inputs were undisclosed. Yet, this secrecy is not an issue for the reader because the content of this paper is not based on completed design optimization study to reach specific design targets under predefined conditions. Instead, it focused on comparison of modeling approaches and corresponding definitions for Aluminum honeycomb under high velocity impact in order to determine which way offers desired accuracy and CPU efficiency for such scenario.

Aluminum honeycombs have been fitted to many points in ballistic protection products with different attributes and shapes. This study discusses on one of them which is responsible for blocking a plate flying with velocity above 1000m/s and reduce the force transmitted to neighbor energetic material down to a point where no pressure induced reaction occurs. Exact details of this energetic layer were certainly undisclosed but overall schematic was given in Fig.3:.

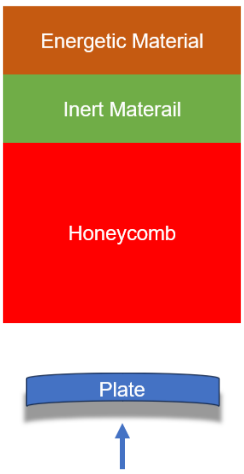

Fig.3: Loading scenario

During the design process, lots of experimental measurement were performed for the functional evaluation of the Aluminum honeycomb during design process that both quantitative (final velocities by ionization pins) and qualitative (reaction status in energetic material, deformed shape of plates) data were recorded for different velocities and contact area. Final thickness of honeycomb layer was not one of the compared values as it attained final thickness that aluminum foil can no more be folded in all cases (densification). These outputs provided required input for building up and tuning a finite element model with solid elements which sustains its validity within a range of impact velocity and mass. This model was later adopted for different honeycomb densities, shapes and loading types and successfully verified for all cases by means of full system tests. Mentioned model consist of fully integrated solid elements (ELFORM=-1) with edge length of 1.1 mm in lateral direction and 1.9 mm in impact direction. Effect of this aspect ratio has been verified in former parametric studies and reportedly gave best accuracy/cost ratio. Interaction between plate and honeycomb was defined by ***CONTACT_ERODING_SINGLE_SURFACE** with SOFT=2, FS(D)=0.35 and DTSTIF=0.048µs. As a material model for honeycomb, ***MAT_126_MODIFIED_HONEYCOMB**, whose parameters defined following comprehensive characterisation tests, was defined.

In case of depiction of any experimental setups in mentioned model verifications, actual dimensions and type of the honeycomb employed and armour details might be revealed which violate confidentiality of the product. Thus, a representative model (Fig.4:) was developed to take basis in all approaches. This model consisted of a surrogate thin plate with overall velocity above 1000m/s that hits honeycomb (26mm thickness) compresses it. Following complete collapse, residual kinetic energy of the plate accelerates upper layers which contains stack of inert and energetic material (only single layer was shown in Fig.4:) Maximum pressure in the energetic material and momentum transferred upper layer were taken as metrics for accuracy evaluation while total CPU time was recorded for the aspect of solution efficiency. Results of the analysis with verified model inputs given above was taken as reference for comparison.

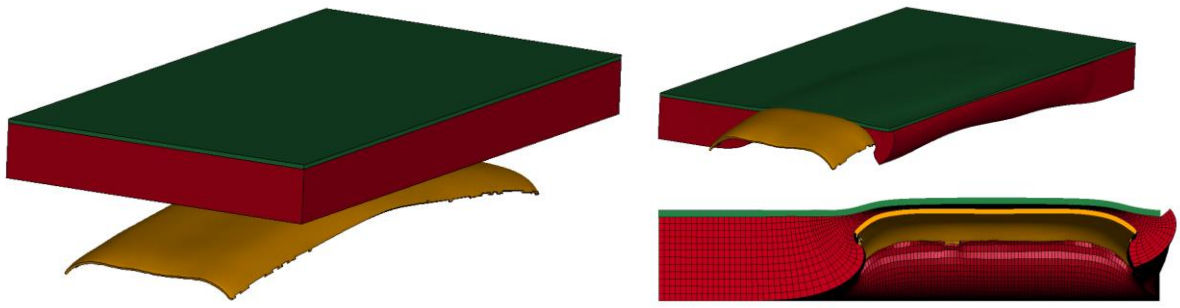

Fig.4: Geometry used in comparative study (left) and anticipated deformation (bottom-right: section view)

All simulation took place in same Windows-based workstation (16 physical 4.3 GHz CPU & 512 GB memory) that run LS-Dyna V13.1 Double Precision MPP solver (INTEL). Region to be deformed in whole model was decomposed in to 16 CPU equally (as much as possible) by slicing all domain parallel to impact direction.

3 Results

3.1 Solid Finite Elements

Though a specific modeling inputs have been verified with tests, effect of mesh size, element formulation and effect of the ***CONTACT_INTERIOR** was investigated within the scope of this study.

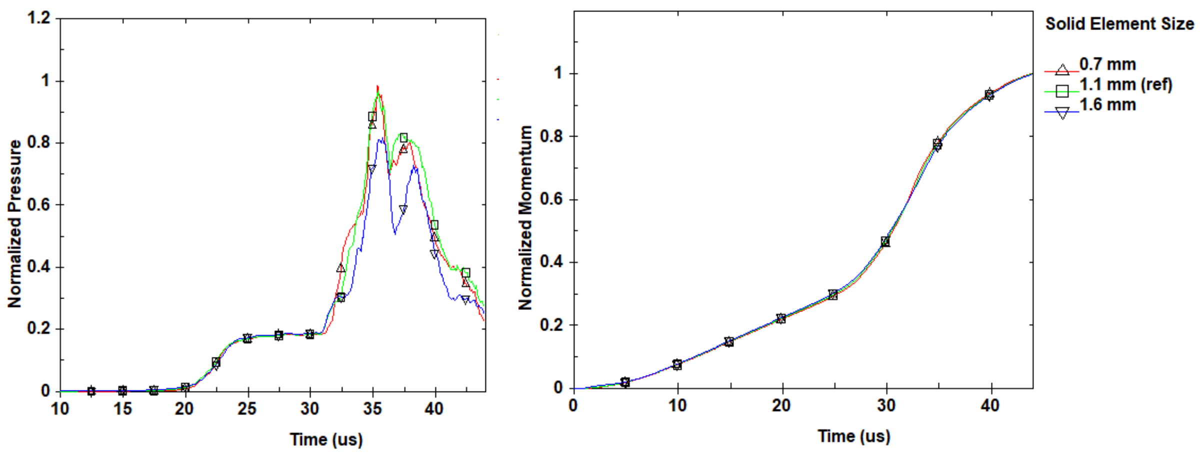

Fig.5: Normalized pressure on energetic material (left) and transferred momentum to honeycomb (right) in finite element models with different mesh size

For mesh sensitivity evaluation, keeping the aspect ratio constant, 3 different element size, 0.7mm, 1.1mm (ref.) and 1.6 mm were adopted whose pressure and momentum curves were given in Fig.5:. According to these results, refining the mesh size further from 1.1mm did not provide significant change in both peak force and pressure accumulation while increased solution time by 41%. Deformation plots, given in Fig.6:, showed no distinctive variation between shapes and compressed thickness. these results verify validity the solid element size used in reference model which will be used in further comparisons.

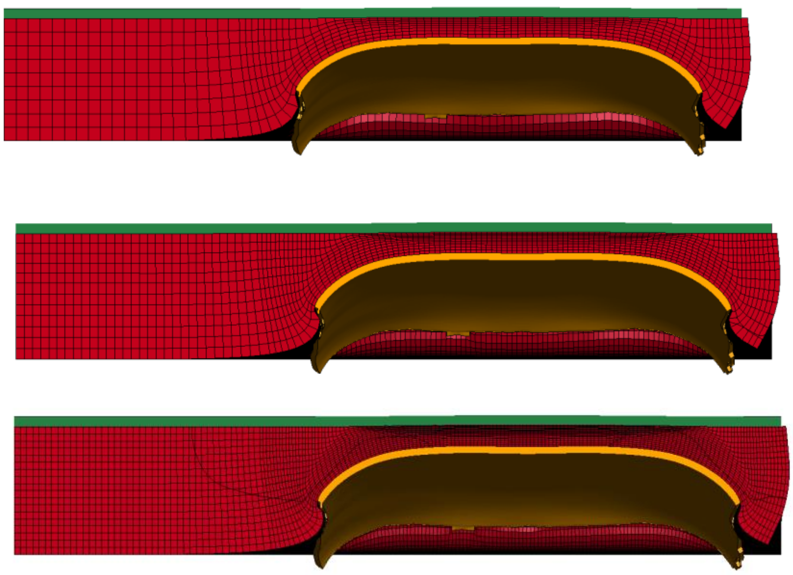

Fig.6: Section view of finite element models with 1.6mm, 1.1mm and 0.7 mm element size respectively at 25µs.

It should be noted that element erosion induced by strain cutoff defined in material model and minimum time step (DTMIN=0.2) initiated after 29 µs in the reference model. This value was reported as 32µs and 24 µs coarse (1.6mm) fine (0.7mm) mesh respectively. Erosion by negative volume in honeycomb was also reported in all cases but in negligible amounts. Percentage of eroded mass appeared as 0.7% which was almost same in all mesh sizes. This result showed effect of element distortion was not influenced by element size as predicted. Such deformation in lagrangian approximation was anticipated considering the former studies, and obviously increased total CPU time in all models by dropping time steps %80 which is maximum limit as mentioned.

Reference model used full integrated S/R solid element (ELFORM=-1) which did not cause any negative volume issue before the cutoffs. However, in the aspect of solution efficiency, reduced integrated models have also been examined and compared. ELFORM=0 and 9, which were developed for the material model utilized in this study (`*MAT_126`), surprisingly led absurd deformation that bottom surface of the honeycomb tangled and violated all contact definition. These formulations were therefore neglected in this study and only ELFORM=1 (conventional 1 point integrated solid) was included as alternative. Fig.7: gives maximum pressure on explosive layer and momentum transferred. Reduced integration decreased solution time by 15% which seems feasible considering negligible difference in pressure and momentum results.

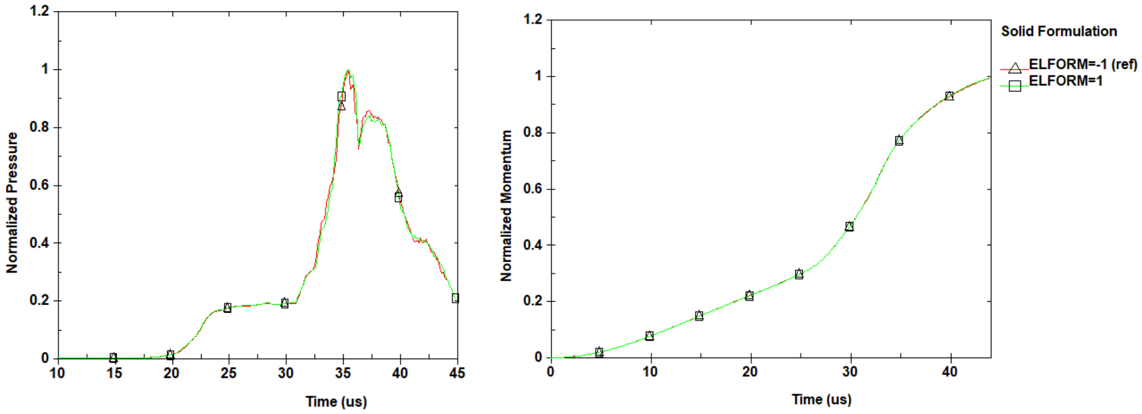

Fig.7: Normalized pressure on energetic material (left) and transferred momentum to honeycomb (right) in finite element models with different full and reduced integrated elements.

`*CONTACT_INTERIOR` is a tool developed for foam-like materials which are subjected to severe compressive deformation. Briefly, it adds some stiffness between interior surface of elements to hinder or even delay element distortion related issues. Effect of this card was evaluated simply by defining the part set included honeycomb. As one can see in Fig.8:, there appears sudden pile up in pressure and significant increase in momentum. In order to understand this effect, deformation was examined that interior penetrations and edge tangling were observed (Fig.9:). Sudden increase in pressure was associated with extreme rigidity appeared at the impact zone which cause transmission of secondary force wave. As it offers ad-hoc rigidity to the elements to avoid negative volume, it causes artificial stiffness in part when element surfaces meet that may lead amplified force as it was observed in this study. Total CPU time was increased 210 % which appears as another reason not to employ `*CONTACT_INTERIOR` modeling honeycomb experienced complete collapse.

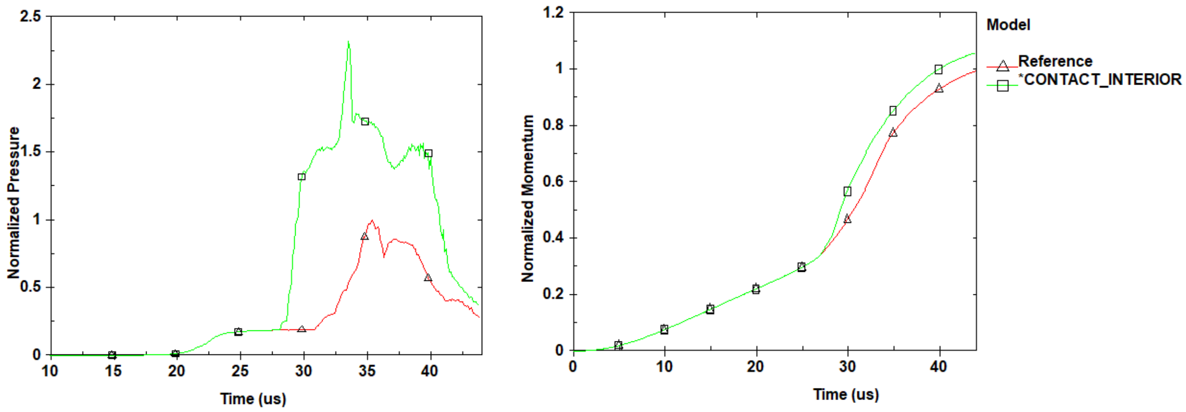

*Fig.8: Effect of *CONTACT_INTERIOR on Normalized pressure on energetic material (left) and transferred momentum to honeycomb (right) in finite element model.*

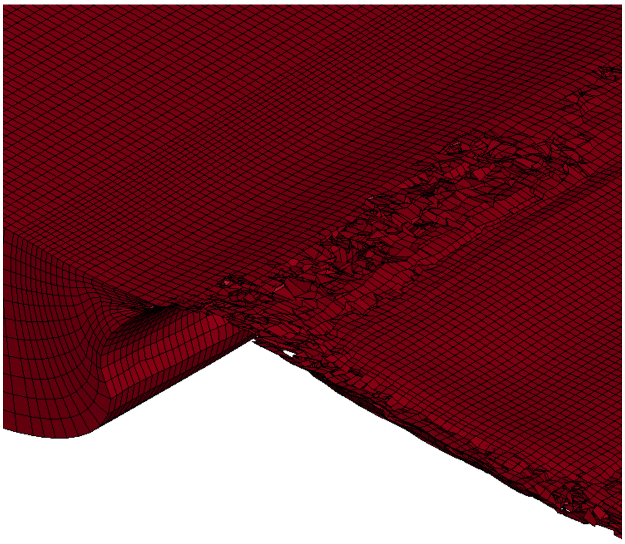

*Fig.9: Element distortions observed in the model with *CONTACT_INTERIOR*

3.2 EFG

Use of Element-Free Galerkin (EFG) method is not a new appraoch for modeling honeycomb material as mentioned. Becasue it had been implemented particularly for mechanical forming without material separation, it was promising to solve many issues related with finite elements like time step variation or extreme deformation-induced over stiffness. EFG nodes has shape function-like spatial interpolation relation between other nodes within a support domain while integration was performed on points in phantom elements. For being vulnerable to negative volume issue as numerical integration takes place within an element whose boundaries deform with material, extreme shape change is still reason for apprehension.

In this study, EFG was employed to evaluate its capability to supersede solid finite element in the perspective of CPU time efficiency. Cubic Semi-Lagrangian kernel was defined in **`*SECTION_SOLID_EFG`** with ELFORM=41 while dilatation parameters were kept as 1.1 in accordance with general rule of thumb.

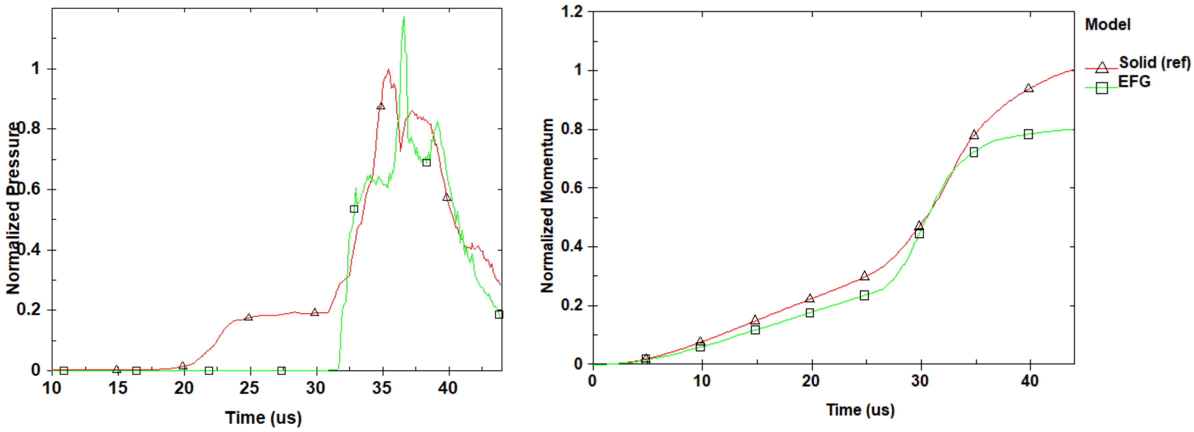

Fig.10: Normalized pressure on energetic material (left) and transferred momentum to honeycomb (right) in finite element and Element-Free Galerkin (EFG) models

When same mesh size was adopted for EFG model, it can be seen that energetic material experienced delayed but sudden pressure evolution. A Plateau (between t=20μs and 32μs) of pressure which was identified with linear elastic phase in honeycomb compression (Fig.2:) was not observed in EFG model. Reason of such absence in pressure is misty because momentum transfer to honeycomb had relatively low but parallel regime which shows force transmission initiated at almost same time. Peak pressure recorded in EFG model was higher (%17) and when deformation was examined (Fig.11:) such incline was explained by erosion of all EFG nodes following negative volume and contact of plate to upper layer. Descent in the slope of momentum at 34μs supported this fact that honeycomb was no longer able to transmit force to upper layers. Loss of densified honeycomb elements was unexpected because EFG nodes were assumed to survive longer or even last as long as solid finite elements.

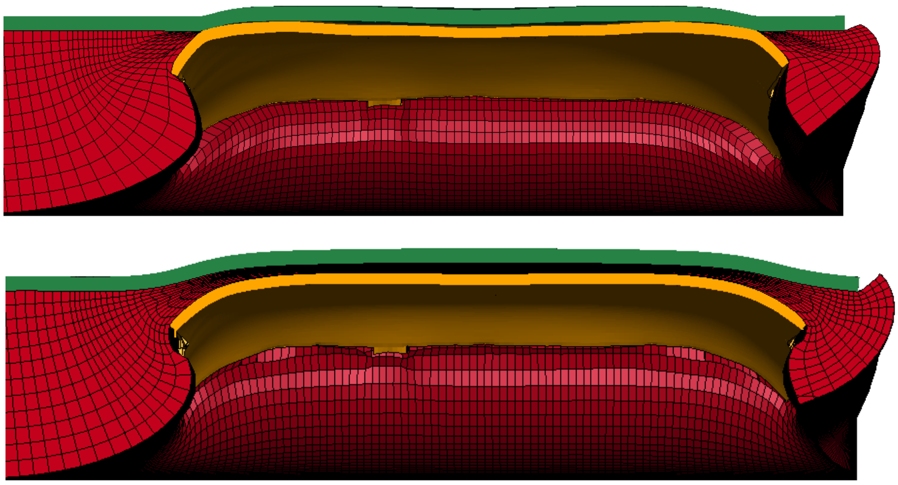

Fig.11: Section view of EFG (up) and reference finite element (bottom) models at 36µs

Effect of mesh size in mesh free methods controversial and mostly depends on loading type and material. Mesh sensitivity was therefore performed that maximum pressure over time detected in energetic material was compared in Fig.12: with deformation plots. It can be seen that element size employed in the first place (1.1mm) was safe (%0.6 increase in peak stress in fine mesh) and there was no need to refine the model to improve numerical accuracy.

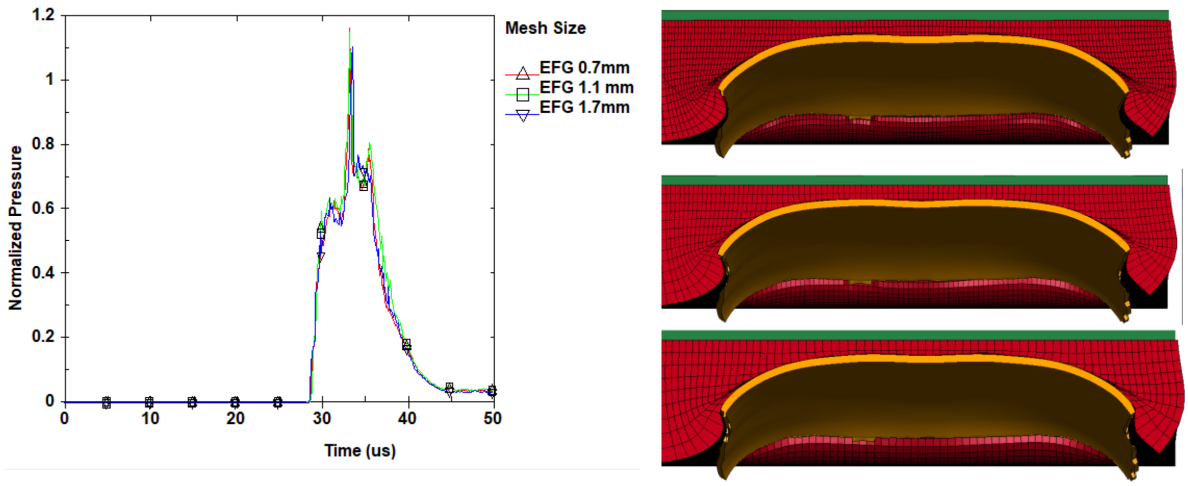

Fig.12: Normalized pressure on energetic material (left) and section view (at 25µs) of EFG model with different mesh size

The reason of considering EFG was its possible enhancement in CPU time efficiency which was given in Table 1. comparatively. With same element size, total solution time was recorded as lower than 70%, which was remarkable. Moreover, when accuracy was compromised slightly by increased element size by 50%, total solution time was reduced down to 57 minutes which is 47% of reference model. Negative volume-induced element deletion in compressed honeycomb was assumed to be main factor of this decline, despite the cost of contact surface update in eroding contacts. Deformation-induced remeshing can be a solution for this material loss which would probably reduce deviation in the peak pressure.

Table 1: Total solution time recorded in EFG models with different mesh size

Model	EFG (0.7mm)	EFG (1.1mm)	EFG (1.7mm)	FE (1.1mm)
Total CPU time (min)	131	83	57	120

3.3 SPH

Smooth Particle Hydrodynamics (SPH) is most widely used mesh-free method due to its ability to solve extreme deformation in structures as well as compressible CFD problems. It completes solution of all weak equations within nodes that no background mesh was forced for numerical integration. SPH, therefore, never yiels issues like negative volume, but it is prone to numerical instabilities especially under tensile loading. Considerably high memory demand, depending on number of DOF and influence domain makes it less preferred in low to medium velocity impact simulations. Modeling honeycomb with SPH nodes has not been general practice in literature probably for that reason. However, as it has been continuously improved and strongly emphasized approach for severe deformation, SPH was also utilized in this study as a candidate method.

As recommended, default SPH formulation (FORM=0) was employed in first simulation which was not completed even after 8 hours. Increase in number of neighbours was forced and times steps descended to lower limit. After some trials, one with Eulerian formulation (FORM=5) successfully terminated surprisingly within 110 minutes, faster than reference model. It should be noted that node to node distance (particle diameter) in lateral direction was 1.0 mm, very close to reference finite element model. Effect of node density was evaluated by changing this value to 0.7mm and 1.5mm while keeping contact stiffness same (DTSTIF).

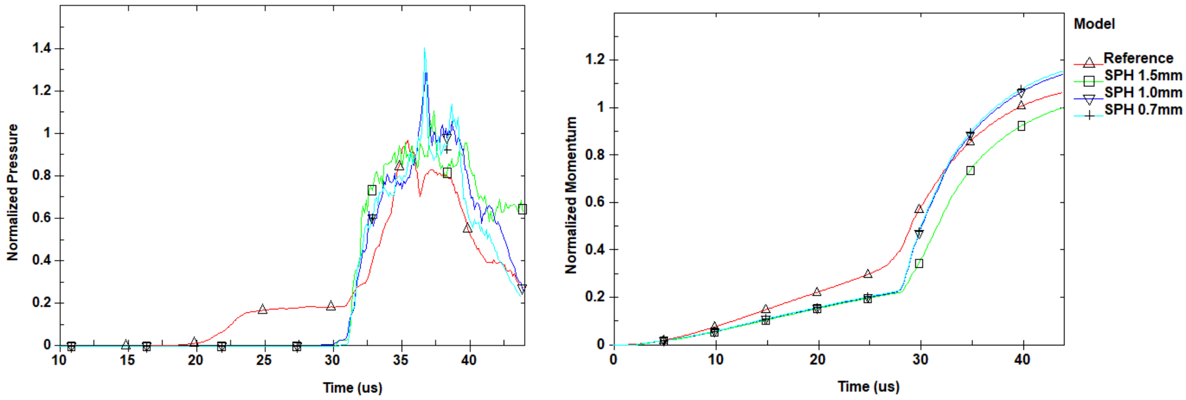

Fig.13: Normalized pressure on energetic material (left) and transferred momentum to honeycomb (right) in SPH models with different node density

Comparative results were given in Fig.13: in which elevated pressure evolution and peak pressure can be seen. Similar to EFG, plateau between 20µs and 32 µs was missing which can be related to nothing but numerical characteristic of mesh-free domain. Peak pressure was 28% and 40% higher than the reference value in the models having 1.0 and 0.7 particle diameter respectively. Despite being not that high, vertical momentums curves of these two models also exceeded reference model prior to the densification phase. As peak pressures seem did not converged even after refining the particle diameter down to 0.7mm, gap between pressure and momentum between results of reference finite element and SPH models would probably increase if mesh density raised. Presence of such steep summit in pressure around 37µs resembles the ones in EFG models which was associated with contact discontinuity due to element loss. However, in this case no deletion in SPH nodes were reported (Fig.14:) and all were stacked up between plate and upper layer. These sudden pressure jumps were related to contact disturbance which can hopefully be solved by adjusting inputs. However, even after possible solution, total CPU time of SPH model with valid particle diameter would still be a drawback. CPU time of the model with particle diameter of 0.7mm was 310 minutes which was significantly higher that reference model (120 minutes).

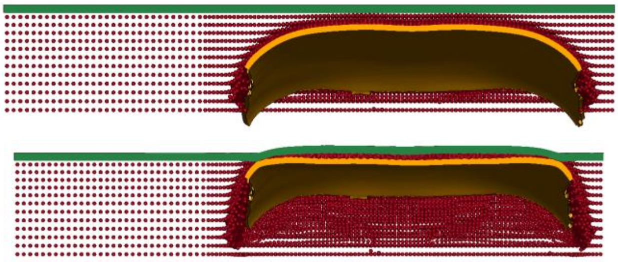

Fig.14: Section view of SPH model at 25µs and (up) and 35µs (bottom)

4 Summary

Available solution approaches for high density Aluminium honeycomb subjected to high velocity plate impact was evaluated in this study. Reference model which consisted of solid finite elements with specific element dimensions, contact definitions and material model had been developed by means of experiments. Results of this model was used to normalize outputs of other approaches for comparison in the aspect of accuracy and CPU efficiency.

After keeping contact stiffness constant, effect of mesh size was found insignificant below 1.1mm. Increasing mesh size on the other hand cause divergence from reference values. Using elements with one-point integration did not change in pressure and momentum outputs remarkably while it reduced total CPU time by 15%. *CONTACT_INTERIOR did not provide any beneficial results as it overestimated pressure and momentum while increased total CPU time.

Element-Free Galerkin (EFG) method was evaluated with different element sizes. Although total CPU time was significantly low compared with finite element and very slight variation was observed by refining the mesh size, peak pressure calculated on energetic material in all EFG models was at least 17% higher than reference model. Together with massive element erosion following negative volume, accuracy concerns appeared. Remeshing should be considered to reduce element erosion and contact disturbances.

Smooth Particle Hydrodynamics (SPH) was a debatable candidate as it is infamous for being CPU and memory demanding method but capable of solving extreme deformations. Maximum pressure on energetic material was found significantly high in SPH which became severe when number of SPH nodes increased. Beside this dependence, total solution time recorded was not promising and eliminated SPH as an alternative approach for modeling Aluminium honeycomb.

5 Literature

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