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Ballistic impact analyses of triangular corrugated plates filled with foam core

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Abstract. The usage of sandwich structure is extensively increasing in lightweight protective structures due to its low density and other useful properties. Sandwich panels made of metal sheets with unfilled cellular cores are found to exhibit lower deflections by comparing to an equivalent monolithic plate of same metal and similar mass per unit density. However, the process of localized impact on solid structures involving plastic deformation, high strain rates, temperature effect, material erosion, etc. does not hold effectively as that of monolithic plate. In present work, the applications of the sandwich plate with corrugated core have been extended to develop optimized lightweight armour using foam as medium of its core by explicit finite element analysis (FEA). The mechanisms of hardened steel projectile penetration of aluminum corrugated sandwich panels filled with foams have been numerically investigated by finite element analysis (FEA). A comparative study is done for the triangular corrugated sandwich plate filled with polymeric foam and metallic foam with different densities in order to achieve the optimum penetration resistance to ballistic impact. Corrugated sandwich plates filled with metallic foams are found to be superior when compared to the polymeric one. The optimized results are then compared with that of equivalent solid and unfilled cores structure to observe the effectiveness of foam-filled corrugated sandwich plate which provides an effective resistance to ballistic response. The novel structure can be the alternative to solid aluminum plate in the applications of light weight protection system.

Keywords: corrugated plate; explicit; FEA; foam; impact; residual velocity; sandwich

1. Introduction

The weights of the parts, during design, are the calumniatory parameter in civil engineering, aerospace engineering and shipbuilding industry. Sandwich panels are extensively and increasingly used due to its lightweight characteristics in above mentioned industries. A sandwich plate is a three-layer structure, comprised of a thick core between two thin, flat face sheets. The core of the sandwich construction keeps the faces apart and stabilizes them by resisting vertical deformations due to its outstanding strength, and also enables the whole structure to act as a single thick plate as a virtue of its shear strength. Development of core materials is evolving till date in order to reduce the weight of sandwich panels (Chang 2004). Sandwich structures are being

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widely used in a number of critical engineering applications, such as vehicles, ships, aircrafts, and spacecrafts, due to their excellent comprehensive characteristics. Thus, studies on metallic sandwich beams, plates, and shells with various cores have received much attention. Recently, the US Navy has been studying application of the laser-welded corrugated-core sandwich constructions (Marsico *et al*. 1993, Wiernicki *et al*. 1991).

The structure suffers to localized impact loading in many applications; hence response of these panels to ballistic load has become a point of interest. Lightweight materials and structures utilized in transportation systems are sometimes subjected to dynamic loads due to impact events or the impingement of shock waves created by nearby explosions. Situations involving impact (The collision of two or more solid bodies) are currently of research interest. Traditionally, this area deals with military applications. However, with advent of technology, severe demands on materials behavior under impact loading are extending its application to various fields of application.

Impact phenomena can be characterized in a number of ways according to the impact angle, the geometric and material characteristics of the target or projectile, or striking velocity. A complete treatment of the impact response of materials and structures and of the geometry of interacting bodies, elastic-plastic and shock wave propagation, hydrodynamic flow, finite strains and deflections, strain rate effects, work hardening, thermal and frictional effects, and the initiation and propagation of failure in the colliding materials. The development of multifunctional materials and structures that provide dynamic load mitigation capabilities in addition to their normal structural requirements are therefore important to a number of fields such as crash protection, petro-chemical safety, infrastructure protection and many military applications.

The mechanical properties of corrugated composite sandwich structures with sinusoidal plate core were studied where the compressive strengths and dynamic response of corrugated metal sandwich plates with unfilled and foam-filled sinusoidal plate cores were investigated analytically and numerically both by Jianxun *et al*. (2013). Metallic sandwich panels with unfilled cellular cores can exhibit superior bending stiffness and strength compared to solid (monolithic) plates of the same alloy and mass per unit area (known as areal density) (Wadley *et al*. 2013). Aluminum sandwich plates with corrugated aluminum core and glued bonds are used extensively in industry and construction, both as structural elements as well as cover plate elements and interior walls. Zhou and Stronge (2008) perform ballistic limit for oblique impact of thin sandwich panels and spaced plates and concluded that sandwich panels are more resistant to perforation during hypervelocity impact than monolithic structures with the same thickness as the face sheets.

Replacing monolithic plates by multi-layered plates either with or without spacing has been a long debate by the researcher for protection against projectile. Empty spaced layers were found to be less compelling at resisting perforation than multi-layered plates without spacing. Post perforation residual velocities of projectile of a layered sandwich with empty core plate are larger than monolithic plate of same areal density (Gupta *et al*. 1997). The effect of type, size or wall thickness of core does not significantly affect ballistic limit whereas perforation was depending mainly upon piercing of sheets. Results indicated that more the blunt the nose shape, higher will be the ballistic limit. The effect of the projectile's nose shape on ballistic limit or energy absorption has been investigated by a number of researchers but this influence is still not completely formulated. For more than two decades, foams have become the sought after materials for researcher. Upon subjected to ballistic impact, the foam exhibits significant non-linear deformation and stress wave attenuation. Open and closed cell structured foams like polyvinyl chloride, polyurethane, polyethylene or polystyrene foams, balsa wood, syntactic foams and honeycombs are commonly used as core materials (Mohamed *et al*. 2014). It has been observed that cracks initiate from the tensile side and propagate to the compressive side within the core in all sandwich structure specimens. Thealuminum foam armors exhibits less dynamic deflection of the backing plate than the baseline in composite integral armor (CIA) with aluminum foam as its core material (Gama *et al*. 2001).The mean crushing force has a linear dependence with the foam compressive resistance of a metallic foam (Santosa *et al*. 2000). Han and Cho (2014) found the target of aluminum foam sandwich plate exhibit effective resistance to 100J impact energy. An important factor affecting material penetration for aluminum foam is the impacting velocity as well as the dissipated energy of a material (Cho *et al*. 2012).

Impact dynamics involving perforation on solid monolithic plate are present and very few studies have been carried out on foam filled sandwich structures. Similar approach is absent in literature in case of foam filled corrugated plate subjected to impact loading. Numerical approach based on FEA offer easy, cost-effective and time-saving way to perform optimization with an acceptable accuracy. Due to complexity of mechanism the FE analysis requires high computational power and mathematical model to validate the mechanism. So the present work deal with numerical and analytical modeling of impact analysis of sandwich plate with triangular corrugated cores with filled polymeric/metallic foam in order to attain an optimized design parameters having the highest resistance to penetration and perforation.

2. Finite element modeling

2.1 Geometrical modeling

A finite element model was developed to analyze the ballistic penetration of triangular foam filled corrugated cores with a 12.9 mm projectile using commercially available ABAQUS/Explicit code (ABAQUS). In order to carry out a comparative analysis, different models are developed which include targets as the solid monolithic plate, equivalent empty corrugated plate and foam filled corrugated plate. The projectiles considered in this research were of ogive nose and conical nose type. All these models are modeled using the dimensions displayed in as shown Fig. 1. The parameters of solid plate correspond to experiment carried out by Piekutowski *et al*. (1996) whereas corrugated parameters are referenced from the work of Dahiwale *et al*. (2015) who carried out the numerical investigation on empty core corrugated plate corresponds to the Piekutowski experiment.

2.2 Material model

The next step which follows the geometrical model is the material model. In this step, the material properties are assigned to each and every parts of the assembled structure. The materials for target and projectile are considered as Al6061-T651 and 4340 Steel Rod, respectively. The input to the material modeling depends on the constitutive model which is being considered for a particular phenomenon. The phenomenon considered in this phenomenon is ballistic impact which is a very complex one. ABAQUS provides various models for the impact analysis which account for different mechanism that occur during impact phenomenon. Various models are considered in FE simulations to account different phenomenon. They are:

1. Mie-Gruneisen Equation of State (EOS model) - To account pressure volume relationship, depending on whether the material is compressed or expanded.

2. Johnson-Cook Plasticity model - To account Strain-rate and adiabatic temperature - dependent characteristics.

3. Johnson-Cook Failure model - To account the ductile damage initiation criterion of material. The material properties available in literature are used as inputs to various models which are given in Tables 1-4.

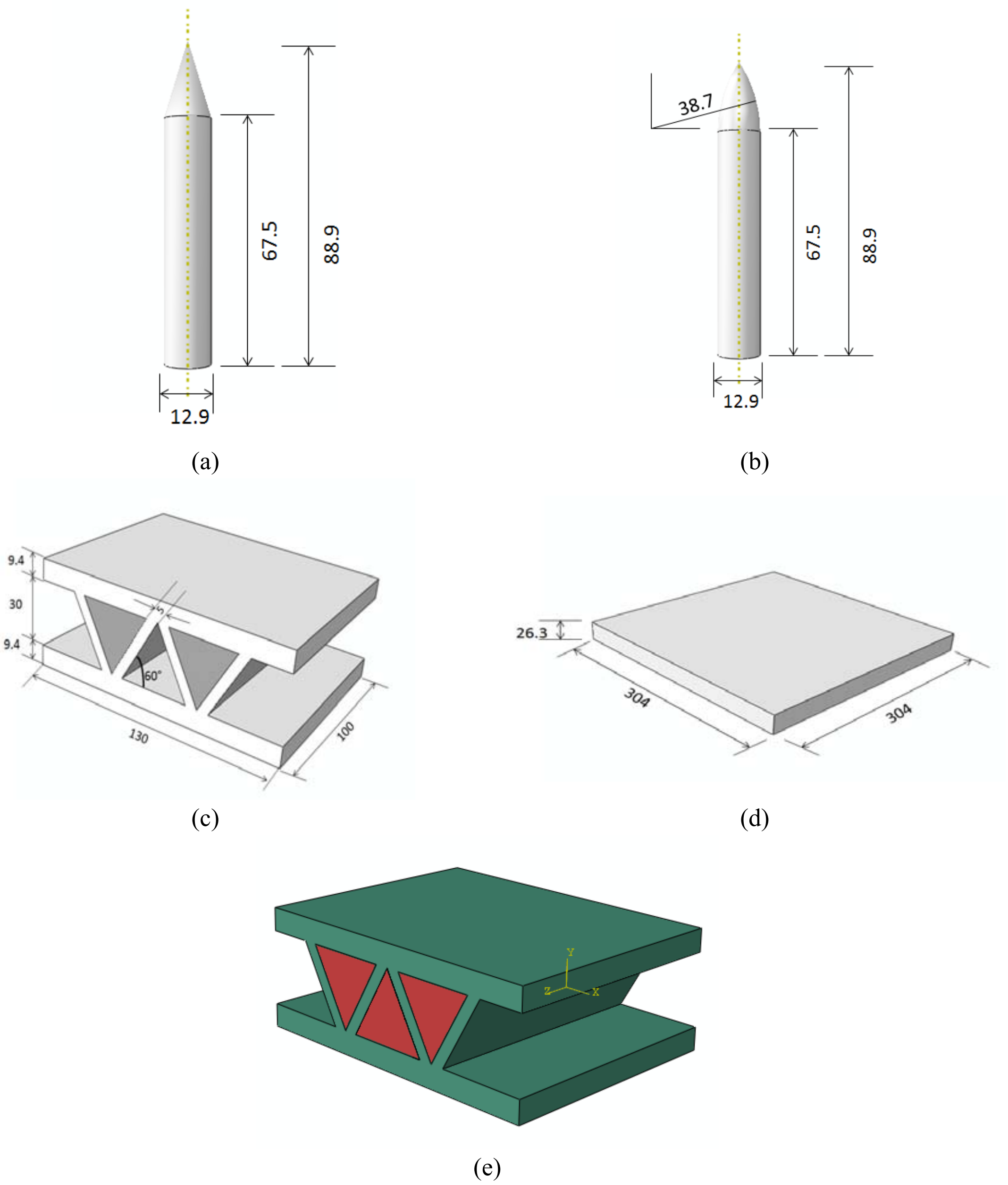


Fig. 1 Physical model along with the dimensions; (a) Conical nose projectile, (b) Ogive nose projectile, (c) Solid target, (d) Empty corrugated target and (e) Foam filled corrugated target (All dimensions are in mm)

Table1 Material properties of steel projectile and aluminum plate used in the FE analysis

Parts	Materials	Young's Modulus (GPa)	0.2% offset Yield Stress (MPa)	Shear Modulus (GPa)
Projectile	4340 Steel	202	1430	80
Target	6061-T651 Aluminum	69	262	26

Table 2 Input parameters for Mie-Gruniesen Equation of state (EOS) model

Parts	Materials	Density (kg/m^3)	Gruneisen coefficient(Γ_0)	Parameter C_0(cm/μs)	Reference Temperature (K)	Specific Heat (J/KgK)
Projectile	4340 Steel	2703	1.97	0.524	293.2	885.0
Target	6061-T651 Aluminum	7830	1.67	0.457	293.2	477.0

Table 3 Input parameters for Johnson-Cook plasticity model

Parts	Materials	*A* (MPa)	*B*(MPa)	*n*	*m*	Θ_{melt} (K)	$\Theta_{transition}$ (K)	C	ε_o
Projectile	4340 Steel	1430	2545	0.7	1.03	1793	293.2	0.014	15
Target	6061-T651 Aluminum	262	162.1	0.2783	1.34	925	293.2	-	-

Table 4 Input parameters for Johnson-Cook dynamic failure model

Parts	Materials	d_1	d_2	d_3	d_4	d_5	Fracture Energy
Projectile	4340 Steel	0.05	3.44	2.12	0.002	1.6	0
Target	6061-T651 Aluminum	-0.77	1.45	0.47	0.0	0.61	0

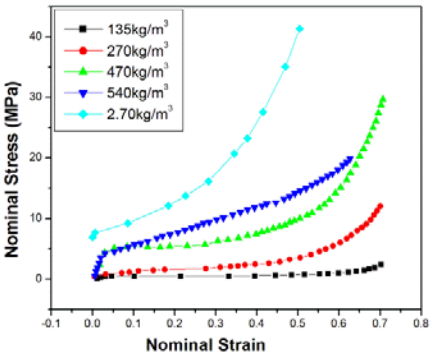
2.3 Core modeling

The core was modeled as an elastic-plastic material. The elastic part of the response of the core was considered as elastically isotropic material defined by the parameters viz. Young's modulus and Poisson's ratio. The plastic part of the response of the core material was modeled using the crushable foam and the crushable foam hardening. The hardening behavior was characterized in terms of uni-axial compression yield by defining stress versus strain. In order to provide input to the experimental uni-axial compression curve, several uni-axial compression stress-strain curve of different foam with different density were studied in extensive from the literatures. Four types of foams were selected where their uni-axial compression stress-strain curve were studied experimentally by different researchers. These were used as input data in while defining crushable foam hardening characteristics. Foams generally taken into consideration in the present simulations are Aluminum foam (commercially known as CYMAT), Polyvinyl Chloride (PVC) foam, Polymethacrylimide (PMI) foam (commercially known as Roha cell) and Polyurethane (PU) foam.

Ballistic impacts of triangular corrugated sandwich plate filled with these four types of foam are extensively studied in this research. And these foams are studied especially for impact

Table 5 Material properties of different foams

Foam Material	Density(kg/m$^{3)}$	Youngs Modulus (GPa)	Poisson's ratio	Compressive Yield Stress Ratio	Plastic Poisson's ratio
Aluminum	270	0.07	0.17	1.5	0
	405	0.03	0.29	1.5	0.133
	470	0.17	0.3	1.5	0.133
	540	0.14	0.3	1.5	0.133
	2.095	0.6	0	1.732	0
PMI	75	0.092	0.3	1	0
	110	0.022	0	1	0
	110	0.16	0	1	0
PU	65	0.005	0	1	0
	90	0.0109	0	1	0
	145	0.0272	0	1	0
PVC	60	0.060	0.32	1	0
	100	0.087	0.3	1	0
	100	0.125	0.31	1	0



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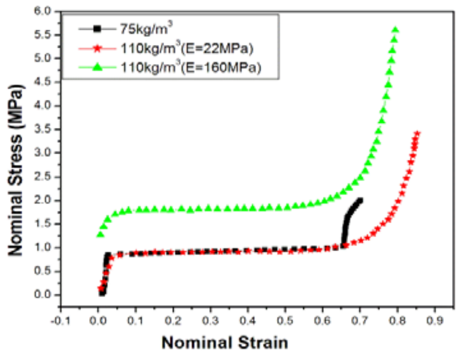

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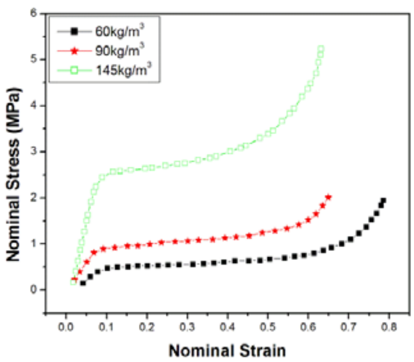

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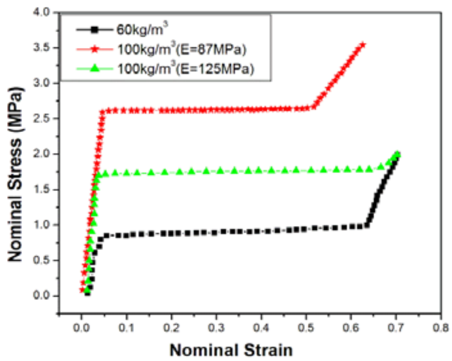


(d)

Fig. 2 Stress-strain curve of different foams; (a) Aluminum, (b) PMI, (c) PU and (d) PVC under uniaxial compression loading resistance (Weihong *et al*. 2010, Lua *et al*. 2008, Carlucci *et al*. 2009). Aluminum foam in one of a kind metallic foam and widely used foam where as other three are polymeric foam. Table 5 represents elastic isotropic properties of the materials. For the plastic behavior of their corresponding uni-axial stress strain curves are illustrated in Fig. 2 (Victor 2007, Ali *et al*. 2011). The data extracted from these curves were assigned to characterize the crushable foam hardening section. For each of the densities provided for the foam each model is analyzed where only the material properties of the foam are varied according to the corresponding densities.

3. Discretization and boundary condition

An extensive convergence study was carried out by Naveen and Panigrahi and their earlier work established that mesh size of 2 mm for both target and projectile gave the converged result. With this mesh size the no of elements for projectile and empty corrugated target are found to be 7616 and 43400 respectively. Element C3D8R are assigned to discretize both projectile and target. Similarly the foam core is meshed with same size of 2 mm leading to 10400 numbers of elements in each foam structure. The reason of taking the same mesh size in core is considered so that the nodal point of core and sandwich plate coincide with each other to a larger extend to provide an accurate result and also it decreases the computational timing to a considerably. Assumed to be as isotropic solid material, element C3D8R is also used to discretize the foam core in the material modeling. The target plate was fixed from all its sides and the projectile was given a velocity of 508 m/s for the analysis. A dynamic explicit simulation was carried out for obtaining the result. In case of the corrugated sandwich plate both unfilled and filled, the projectile was imparted on two points namely the Web Impact and Base impact.

4. Results and discussions

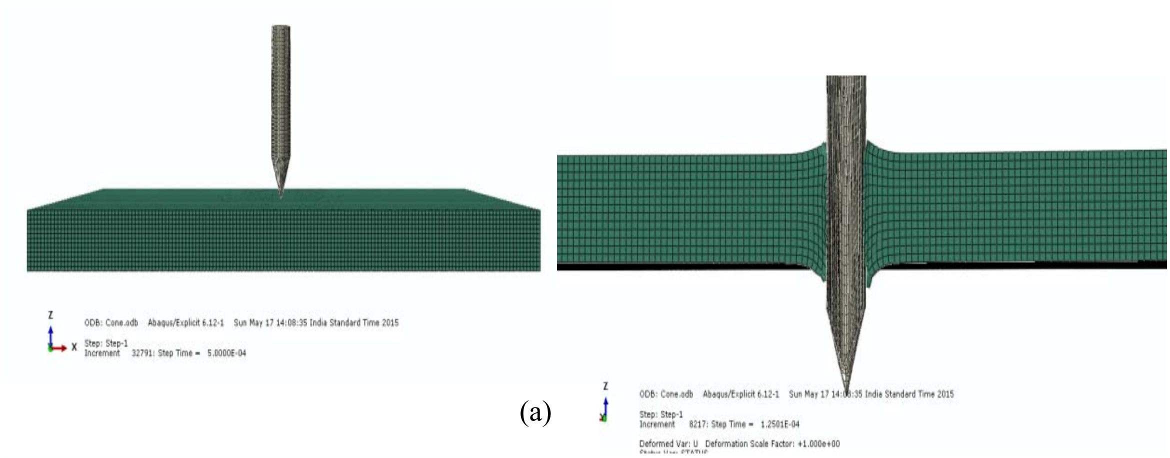
Impact responses of sandwich plate with and without core materials are studied. Results from each simulated model such as solid monolithic plate, empty core corrugated plate and foam core each type of foam were analyzed. Each type of foam corresponding to their different densities, simulation results is analyzed to find the optimum material parameter to evaluate the maximum resistance to the projectile. The perforation process is being captured and depicted in Figs. 3 and 4 corresponding to their assembled model. The important thing is to observe here the type of failure in the sandwich plate. The aluminum plate fails in ductile mode as described by Naveen and Panigrahi in their research whereas the foam fails according to its stress-strain nature. In order to be more elaborate failure of foam core is being separately depicted in Fig. 5 which shows the foam on impact first densifies and upon reaching the maximum point it fails.

4.1 Impact response of sandwich plate filled with aluminum foam

The velocity versus time plot for aluminum foam core model was plotted for different densities as depicted in Fig. 6. Densities between 270 to 540 kg/m^3 shows no appreciable change in residual velocities but Aluminum with 2.7 kg/m^3 which is a very special foam of aluminum used in the grenade with superior properties shows the least residual velocity. Thus this foam provides the maximum resistance to the web impact of foam core corrugated structure.

4.2 Impact response of sandwich plate filled with PMI foam

PMI foam commercially known as Rohacell, shows no change at all due to variation of densities or material parameters. Three grades considered in the analysis show almost the same residual velocity to web impact of foam filled corrugated plate as seen in Fig. 7. But by obtaining the data from the analysis PMI with 110 kg/m^3 and E=22 MPa gives the lowest residual velocity of all three PMI foam. Though the variation is not so appreciable, but it can be considered as the optimum one.



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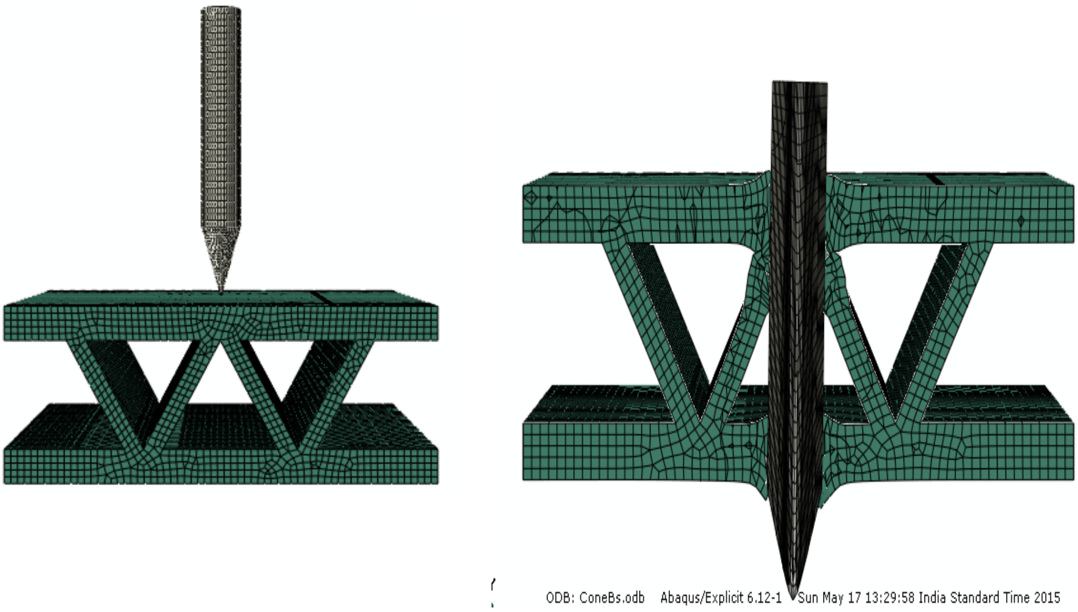

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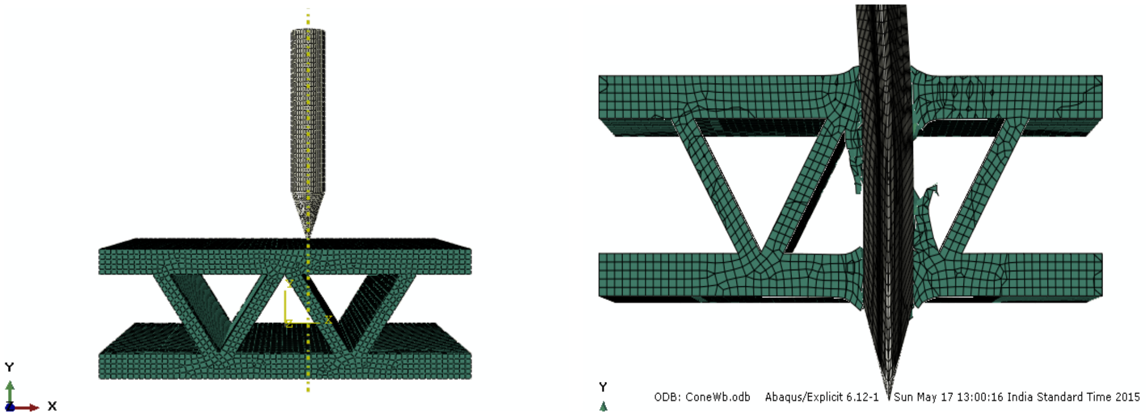
Fig. 3 Deformed shape of the discretized model (without core) due to impact response; (a) Solid plate impact and (b) Empty corrugated plate base impact



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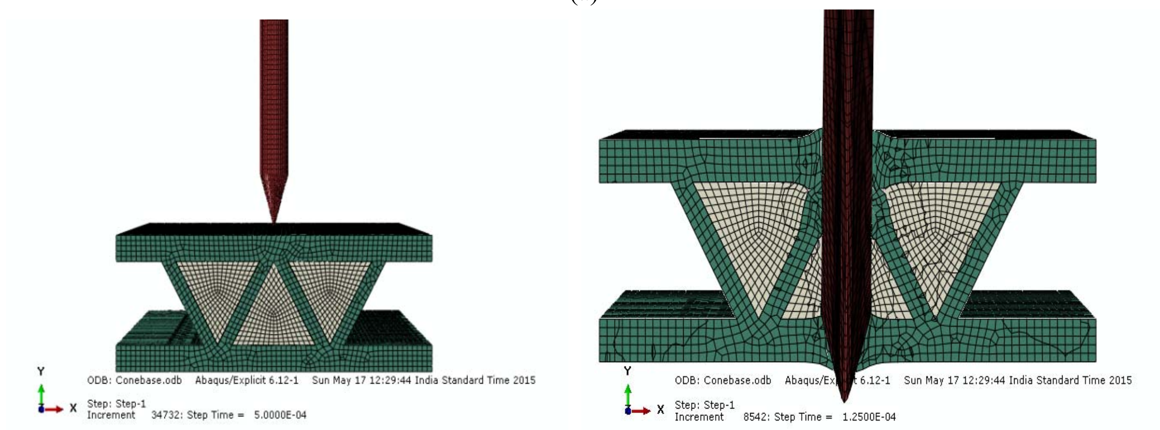

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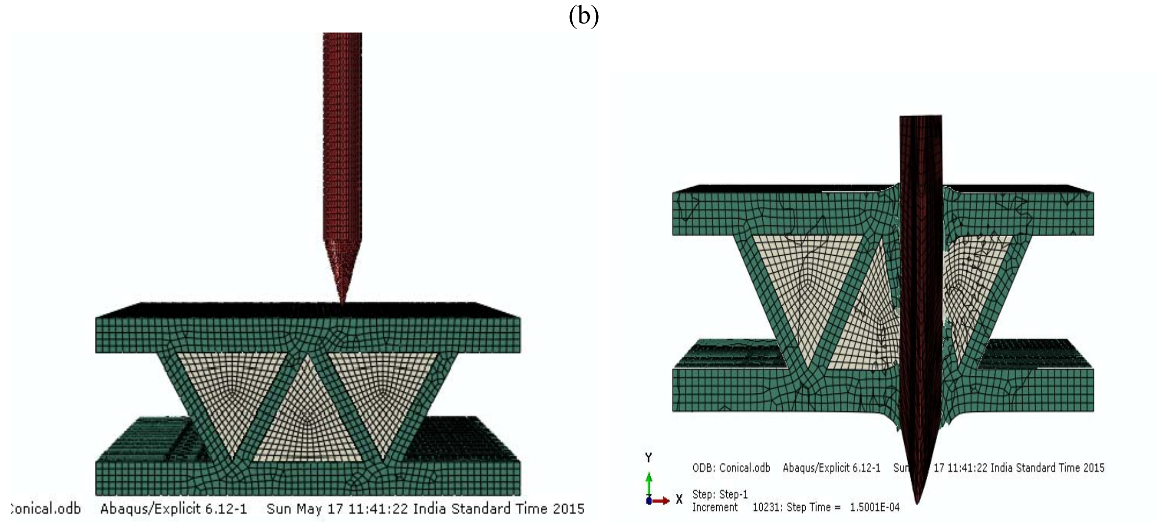

(c)

Fig. 4 Comparison of deformed shape of the discretized model (with and without core) due to impact response; (a) Empty corrugated plate web impact, (b) Foam filled corrugated plate base impact and (c)Foam filled corrugated plate web impact

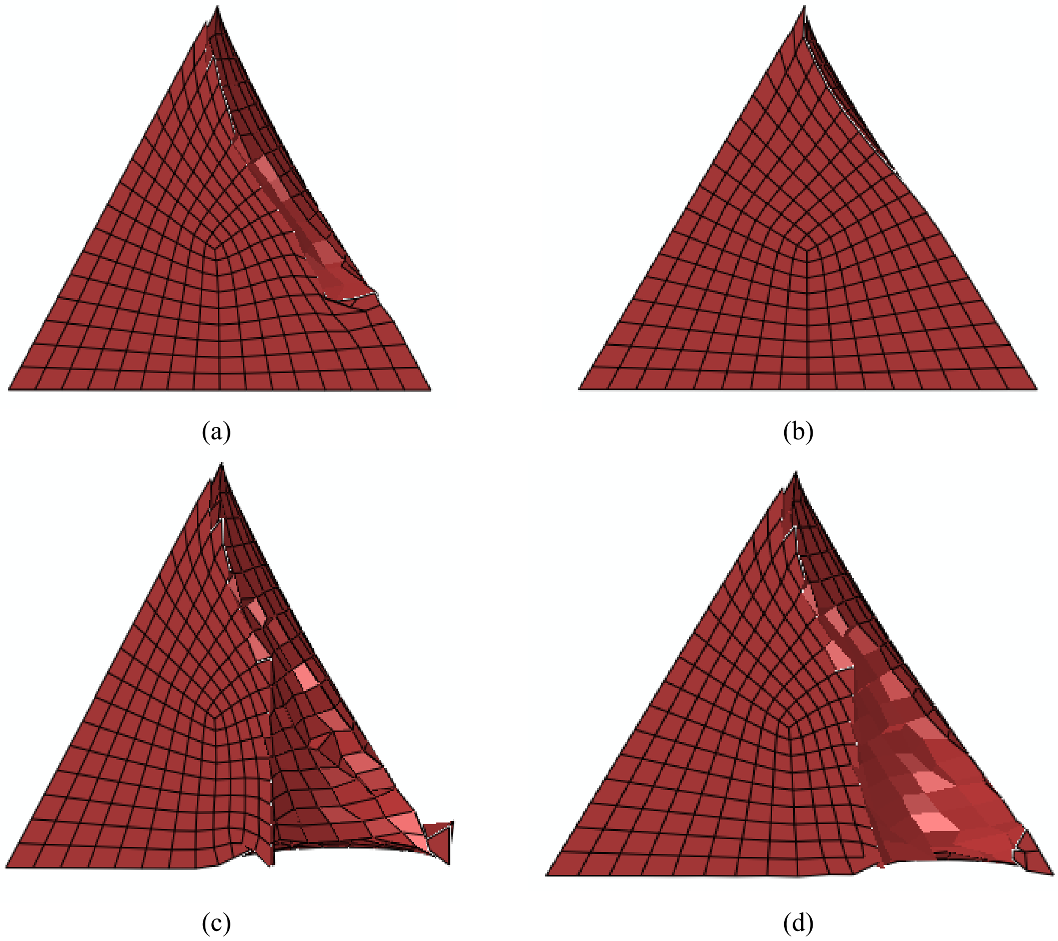

Fig. 5 Foam failure on web impact at different time interval; (a) 25μs, (b) 75μs, (c) 150 μs and (d) 200μs

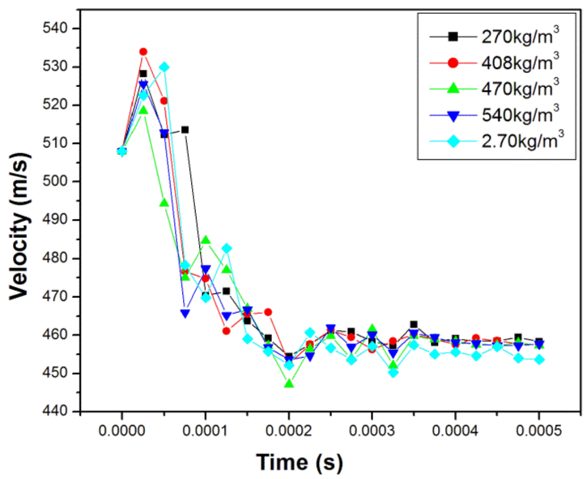

Fig. 6 Velocity-time response for projectile impacting on Aluminum foam core corrugated sandwich plate

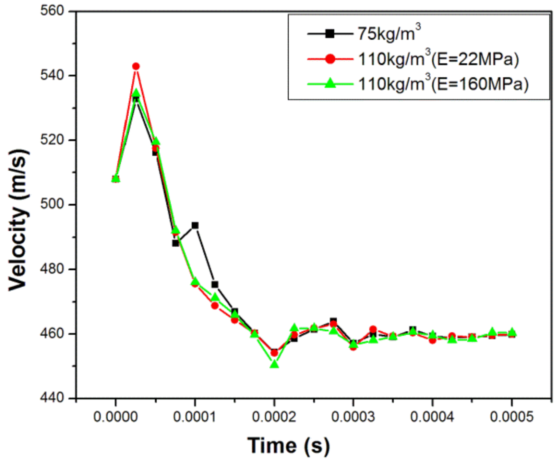

Fig. 7 Velocity-time plot for projectile impacting on PMI foam core corrugated sandwich plate

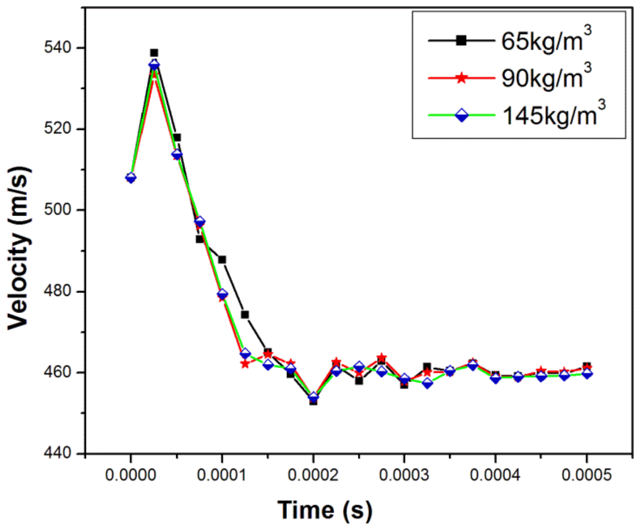

Fig. 8 Velocity-time response for projectile impacting on PU foam core corrugated sandwich plate

4.3 Impact response of sandwich plate filled with PU foam

The residual velocities of the projectile subjected to web impact of foam core corrugated plate filled with PU foams of three different densities are plotted in Fig. 8. PU foam is also giving the same residual velocities for all three different densities. But an appreciable vary in residual velocity can been observed for PU of 145 kg/m^3 grade depicted in green line. Thus this PU foam can be considered as the optimum of other two PU foam grade.

4.4 Impact response of sandwich plate filled with PVC foam

In this analysis PVC foam three different grades are analyzed to the web impact of foam filled

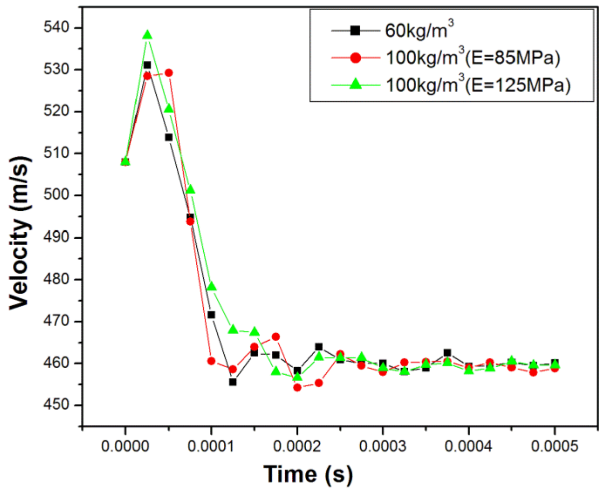

Fig. 9 Velocity-time response for projectile impacting on PVC foam core corrugated sandwich plate

corrugated core sandwich structure. The projectile impact behavior plotted as velocity versus time curve can been seen in Fig. 9. Similar to PU and PMI foams, PVC also does not show any appreciable variation in residual velocities due to different density and material parameters. Carefully observing the red line, PVC with density 100 kg/m^3 and E=85 MPa shows the least residual velocities of all PVC foam. Thus it can be considered as the optimum one.

Of all the four analysis, we can come to an agreement that polymeric foams do not show any appreciable changes to perforation resistance due to variation of density whereas metallic foam, Aluminum foam shows some variation to resist perforation. In order to validate this optimum result of all the foams are taken and plotted in a single plot given in Fig. 10 to analyze the best possible foam to get the maximum resistance in foam filled corrugated core sandwich structure. As it can be derived from the figure, Aluminum foam gives the least residual velocities among all the other polymeric foam. Thus Aluminum foam is found to be the best possible solution to achieve maximum resistance to ballistic perforation on foam filled corrugated sandwich plate.

4.5 Effect of nose shape of the projectile

The numerical results are obtained for both the projectile shape in two impacts for each and for the solid plate. The velocity versus time graph are plotted for both ogive-nose and conical-nose projectile separately. From the velocity-time graph for ogive nose represented in Fig. 11, we can clearly see that the residual velocity of projectile in case of web impact on foam-filled corrugated plate represented in light blue line comes nearly to the residual velocity of solid plate. Whereas in other case the residual velocity is not as effective as solid core which matches with the findings of other studies that empty corrugated plates are not effective as the equivalent monolithic plate subjected to impact analysis. But foam-filled corrugated cores sandwich plate is as effective as the solid plate in ballistic resistance to an ogive-nose projectile.

For conical-nose projectile, the velocity-time graph as shown in Fig. 12 suggests that the residual velocity of the projectile on web impact with foam-core corrugated sandwich plate is more effective than the solid plate. The residual velocity for web impact on foam-core represented in blue is lesser than that of solid monolithic plate represented in black line whereas in other cases it shows similar behavior as that of impact in ogive-nose projectile.

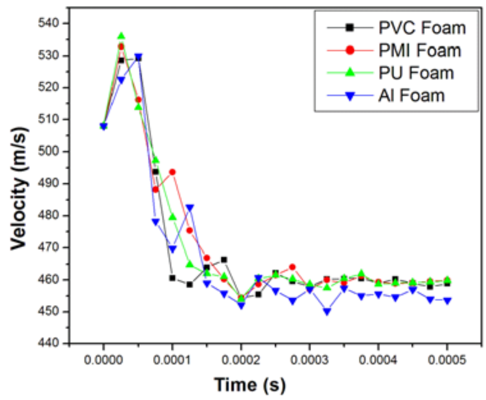

Fig. 10 Comparison of velocity-time response for projectile impacting on different foam core corrugated sandwich plate

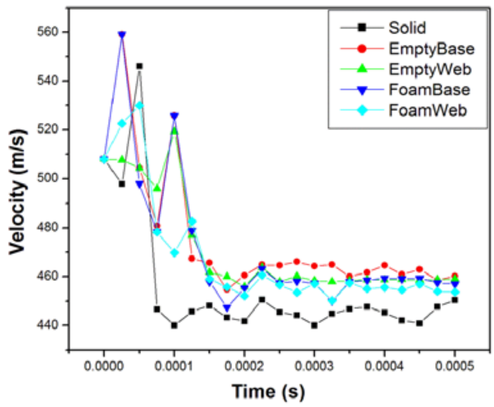

Fig. 11 Velocity-time response for ogive-nose projectile for a varied impact

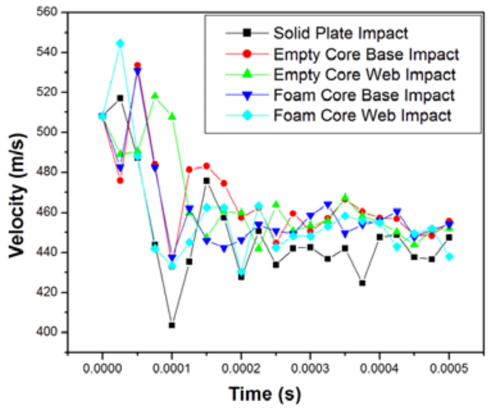

Fig. 12 Velocity-time response for conical-nose projectile for a varied impact

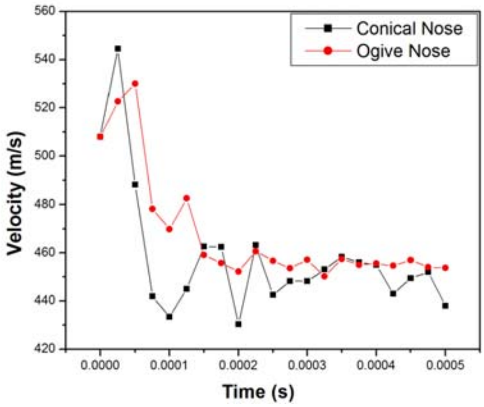

Fig. 13 Comparison of velocity-time response for conical-nose and ogive-nose projectile due to web impact

By comparing the velocity versus time of optimum results of both conical-nose and ogive-nose projectile on a single platform, it can be seen in Fig. 13 that the residual velocity of conical nose in black line is appreciably lesser than that of ogive-nose projectile. Thus foam-filled triangular corrugated sandwich plate gives the maximum resistance to the conical projectile.

5. Conclusions

A dynamic explicit FE analysis has been carried out for the analysis of foam filled triangular corrugated sandwich plate subjected to ballistic impact. The analyses were performed for different polymeric and metallic foams with different densities. A comparative study has been studied out on the foam filled corrugated sandwich plate to analyze the effectiveness of the foam. The objective of the simulations on different types of polymer is to find out the best suited foam to obtain maximum resistance to ballistic load. Then the comparative study on the best suited foam was carried out where it was compared with the analysis of equivalent solid plate and empty corrugated plates. The velocity versus time plot helps to analyze the effect of cores. Followings are the major observations made from the analysis.

• Of all the major foams selected, sandwich plate filled with PU, PMI and PVC foams, shows insignificant difference in the residual velocities with varied densities.

• Further, it is observed that the aluminum foam was found to give the best result to ballistic resistance, thus metallic foams are better than that of polymeric foam.

• During perforation, the foam deforms and densifies until it reach the ultimate yield stress and then crushed and the projectile penetrate through it. The failure is according to the ideal stress-strain characteristics of foam.

• In the comparative study performed with ogive-nose and conical-nose projectile and with that of solid monolithic and empty corrugated structures, the foam filled corrugated sandwich plate shows the best results of ballistic resistance.

• In the case of Ogive-nose projectile web impact, the residual velocities reaches near to that of solid monolithic plate thus giving effective ballistic resistance as that of solid plate whereas as already analyzed that empty corrugated plates are not as effective as equivalent solid plate.

• For conical-nose projectile impact the foam filled corrugated cores with web impact gives the lesser residual velocity than that of equivalent solid monolithic plate. Thus foam filled triangular corrugated sandwich plate gives the optimum ballistic resistance to conical-nose projectile.

• From the above analysis, one can easily conclude that foam filled triangular corrugated sandwich plate is as effective as that of equivalent solid monolithic plate. Thus it can be of greater importance in the application of light-weight protection system. With better bending stiffness than solid monolithic plate, greater reduction in weight and now effective to ballistic impact as that of solid plate, foam filled corrugated sandwich plate can opted as an alternative where solid aluminum plate are considered.

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