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Instrumented ballistic performance of jute/epoxy sandwich with functionally graded rubber core

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Abstract: The qualitative analysis of instrumented ballistic impact for jute-epoxy sandwiches with fly ash reinforced functionally graded (FG) flexible, compliant rubber core is presented. An attempt is made to study the influence of fly ash weight fraction, jute orientation and core to total thickness (C/H) of sandwich on ballistic performance. Experiments are designed based upon L9 orthogonal array. Analysis of variance (ANOVA) is performed on recorded data to investigate the influence of parameters on ballistic response. An optimal parameter combination is determined leading to higher energy absorption and lower energy required for skin pullout by the bullet. A correlation derived from the results of Taguchi experimental design is proposed as a predictive equation for estimation of energy absorption of sandwiches. Furthermore, for arresting bullet optimum stack thickness of sandwich configuration is presented. Finally, the potential benefits for using such materials as a replacement for sand bags in guarding posts is highlighted.

Keywords: ballistic impact; functionally graded; FG; sandwich; Taguchi; ANOVA.

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1 Introduction

Functionally graded materials (FGMs) are built in such manner that their microstructures vary gradually with location within the material (Chakraborty et al., 2003; Mukherjee and Paulino, 2003). As a consequence of this microstructure non-uniform distribution its properties change from point to point within the composite (Cannillo et al., 2007). This new concept of engineering material created in the early '90s allows designers to seek new applications in wide fields. Achieving gradation is much simpler with particulate filler because of their inherent isotropy. There is a vivid literature available on obtaining gradation in syntactic foams addressing studies regarding compressive (Bunn and Mottram, 1993; Gupta et al., 2001), impact (Kim and Oh, 2000) and hygrothermal (Ishai et al., 1995; Gupta and Woldesenbet, 2003; Karthikeyan et al., 2001) properties. Some studies on the mechanical (Gupta et al., 1999, 2002; Corigliano et al., 2000) properties of syntactic foam core sandwich composites are also available.

Sandwich composites are produced by attaching two thin but stiff skins to a lightweight thick core. These materials have high specific strength and bending stiffness (Vinson, 1999). Sandwich composites are commonly used for aerospace, marine and other structural applications including various types of transportation vehicles and packaging. Because of geometrical advantage offered by sandwiches, these structures are widely used as energy absorbing systems subjected to impact loads. A broad classification of the experimental treatment of impacts can be performed by distinguishing between in low, medium and high impact velocity events (Naik, 2008; Hosur et al., 2004). During service, sandwich structures may encounter high-velocity impacts from low weight debris being very sensible to such loads. Despite extensive research on sandwich structures, their impact behaviour is still not fully understood (Aktay et al., 2005; Brenda et al., 2010). Lightweight composite sandwich panels, consisting of fibre reinforced polymer face sheets and polymeric foam core, are becoming more widely used in military vehicles because they offer greater load-bearing capabilities per unit weight and easier maintenance. In some instances, these composite sandwich panels may be subjected to high velocity ballistic impacts by bullets and flying debris from a nearby explosion (Hoo Fatt and Sirivolu, 2010). Polymer composites are used extensively in sandwiches as they retard the projectile by reducing its kinetic energy in ballistic impact (Morye et al., 2000). Projectile impact studies on polymer composite sandwich panels have been mainly concentrated in the low velocity impact regime because of its association with barely visible impact damage (Edgren et al., 2008; Karger et al., 2007; Meo et al., 2005) and finding the panel's ballistic limit (Hampson and Moatamedi, 2007; Ben-Dor et al., 2005; Olsson, 2000; Tarim et al., 2002; Findik and Tarim, 2003). There are very few papers which deal with the issue of high velocity impact of composite sandwich panels. One of the earliest and most comprehensive studies on high velocity projectile impact is on perforation of E-glass woven roving face sheet and foam core sandwich panels (Wen et al., 1998). Few researchers studied sandwich panels with a core height comparable to the face sheet thickness (Skvortsov et al., 2003; Velmurugan et al., 2006). One of the prime materials used for cores in sandwiches in many applications due to its high energy absorbing characteristics, high flexibility, excellent puncture and tear resistance and good adhesion to fabrics is natural rubber (NR) (van Baarle, 2003). Because of these obvious reasons NR has been extensively used as tyres and coated fabrics in many applications (Wootton, 2001; Fung, 2002). Various parameters for ballistic impact were investigated with NR coated fabrics in recent past (Ahmad et al., 2007; Cunniff, 1992; Cheeseman and Bogetti, 2001; Briscoe and Motamedi, 1992; Bazhenov, 1997; Lee et al., 2003; Tan et al., 2005; Chitrangad and Rodriguez-Parada, 1993; Harpell et al., 1986). Wu and Sun (1996) and Shipsha et al. (2003) investigated different failure modes of sandwich beams and suggested that these structures can be upgraded using new materials. Utilising a functionally graded (FG) core in sandwich panels is increasing because of their capabilities in reducing thermal and residual-stresses induced between the face sheets and core materials in comparison to conventional sandwich panels. Venkataraman and Sankar (2003) indicated that a graded core expressively could reduce the face sheet-core interfacial shear stresses while some papers demonstrated the possibility of reducing impact damage in FGMs using different numerical models (Nakamura and Wang, 2004; Quek et al., 2010; Lee et al., 1991; Sun and Wu, 1991; Frostig and Thomsen, 2004; Khalili et al., 2007).

As many of the polymeric systems for developing FGMs are generally associated with the tag of expensiveness, it is decided to examine the gradation in composition and its subsequent behaviour under ballistic impact when an abundantly available lower density possessing fly ash is used as filler material for the core. Fly ash is a fine particulate waste product derived during generation of power in a thermal power plant. These have aspect ratios closer to unity and hence are expected to display near isotropic characteristics. These are inexpensive and possess good mechanical properties. When used with well established matrix systems, these help in reducing the cost and either retain or improve desirable and specific mechanical properties. It has attracted interest (Kulkarni et al., 2002; Ferrigno et al., 1978) lately because of the abundance in terms of volume of the material generated and the environmental-linked problems in the subsequent disposal. These mainly consist of alumina and silica which are expected to improve the composite properties. It also consists to some extent, hollow spherical particles [termed as cenospheres (Mohapatra and Rajagopala, 2001; Pedlow and Torrey, 1978)] which aids in maintenance of lower density values for the composite]. This feature is of considerable significance in weight specific applications. As the fillers are of near spherical shape, the resin spread is better. Developing newer and utilitarian systems using ashes displaying near isotropic properties should be an interesting and challenging task (Kulkarni and Kishore, 2002). Further, in this effort for the skins too, instead of well explored man-made fibres (like glass, carbon, aramid, etc.), it is decided to employ a fairly strong naturally occurring material by the name 'jute fibre'. These are known for their inexpensiveness. Jute reinforced plastics offer attractive propositions for cost-effective applications (Mohan et al., 1983). These in the form of laminates have much better properties than their neat resin counterparts (Shah and Lakkad, 1981). Better properties of woven jute fabric reinforced composites demonstrated their potential for use in a number of consumable goods in the earlier literature (Gowda et al., 1999). Substantial increase in flexural modulus and strength with small amount of reinforcement of unidirectional jute has been reported in the earlier works carried out by researchers (Mohan and Kishore, 1985).

A thermosetting epoxy is chosen for fabricating the skins. To produce the gradation in core, the lightness and a slightly varying density owing to the existence of different morphologies for the ash is fully made use of to yield a matrix system consisting of rubber. Here again, more from the standpoint of cost, availability and the scarce literature (Apetre et al., 2003; Sankar, 2001) prompted for going in for a naturally occurring elastomeric material known by the name 'NR'. However, little is known on the ballistic performance of NR reinforced with fly ash as a core for jute/epoxy sandwiches. Qualitative understanding on the ballistic impact and stab resistance performances for these sandwiches with FG rubber core is not yet available in open literature (Birman and Byrd, 2007; Chin, 1999). Hence, for the present study, sandwich composites made up of fly ash reinforced rubber core and jute epoxy skins are fabricated and tested for instrumented ballistic impact behaviour. Sandwich preparation and testing is done according to L9 OA (Montgomery, 2001; Ross, 1995). Two ratios, area of rear side of hole to area of front side of hole (A_R/A_F) and energy availability in bullet for skin pull out to area of rear side of hole (A_S/A_R) are used to characterise the damage during ballistic impact. The study considers three factors that could influence the impact behaviour, namely, weight fraction of fly ash (W), orientation of fibres in jute fabric (O) and finally C/H ratio (R) of sandwich. Average values of minimum of five replicates are statistically analysed. Focus of the present investigation is to find the influence of factors on ballistic response and to establish correlation between them.

2 Experimental

2.1 Materials

The matrix system consists of natural latex supplied by Karnataka Forest Development Corporation Ltd., Rubber division, Sullia, Karnataka, India. The density of latex is found to be 1,060 kg/m^3. The filler, viz., fly ash is obtained from Raichur Thermal Power Plant, Raichur, India. This ASTM class 'C' fly ash with bulk density of about 900 kg/m^3 is found to consist of a mixture of solid and hollow spheres of assorted sizes. Energy dispersive spectroscopy of the fly ash sample revealed the main constituents to be silica (63%) and alumina (26%) (Kishore et al., 2002).

2.2 Plan of the experiment for ballistic impact test

Experiments are planned, as briefly stated earlier on, based on L9 OA (Montgomery, 2001). For the present study, material parameter chosen for the experiments is fly ash weight fraction (20%, 30%, 40%) while geometrical parameters are orientation of jute fabric (0°/90°, 30°/60°, 45°/45°) and C/H ratio (0.4, 0.6, 0.8). Table 1 indicates the factors and their level. Difficulties are observed in concern with processing (stirring the mixture of filler and ash) of FG cores for more than 40% of ash addition. For selecting levels for jute orientation a thought is given with reference to earlier published work which discusses decrease in load bearing capacity with increase in orientation angle. Levels for C/H ratios are chosen to present influence of skins as well as core thickness in a profound manner, if any. In the available literature it is shown that the thickness of the core is having a strong influence on the system's response (Mead and Markus, 1968).

Table 1 Factors and levels selected for the present study

Factors levels	*Weight fraction of fly ash (%) (Factor 1)*	*Orientation (°) of jute fabric (Factor 2)*	*C/H ratio (Factor 3)*
Level 1	20	0°/90°	0.4
Level 2	30	30°/60°	0.6
Level 3	40	45°/45°	0.8

The experiment consists of nine [equivalent to 27 experiments in result effectiveness (Montgomery, 2001; Ross, 1995)] set of tests (75 samples). Statistical analysis is employed with the objective as smaller as the better for the impact characterising ratios (higher energy absorbing capacity). Subsequently, analysis of variance (ANOVA) of the results is performed to identify the factors that are statistically significant. With the mean effects plot and ANOVA analyses, the optimal combinations of the parameters are proposed. Furthermore, a confirmation experiment is conducted to verify the predicted values from the regression model with their experimental counterparts. Finally, proven combination of sandwich's stack thickness is optimised to completely arrest the bullet.

2.3 Processing

For processing of FG cores, conventional casting technique is utilised. Fly ash, the filler used for core a mixture of solid (grey ash particles – 2.5 g/cm^3), hollow (cenosphere – 0.5 to 0.6 g/cm^3) and composite particles (plerosphere – 0.8 to 2.0 g/cm^3) possessing different densities having resemblance to spherical form to a larger degree. Presence of gradation in prepared specimens is expected due to these variable density particles present in fly ash which settle while solidifying at different depths. A measured quantity of natural latex is mixed with the pre-weighed amount of fly ash, sulphur (vulcaniser) and zinc oxide (catalyst) (Blackley, 1997) by adopting gentle stirring for about one hour. The mould employed for preparation of core specimen (350 mm × 350 mm × 10 mm) is completely covered on all sides with teflon sheet. Subsequently, silicone releasing agent is applied to facilitate ease of removal of the cast sample at a later stage. The mixture is then slowly decanted into the mould cavity followed by curing at 90°C in an oven for about five to six hours. The cured core sample is removed from the mould and the edges are trimmed.

As regards the sandwich skins, a bi-directional woven jute fabric procured from M/S Barde Agencies, Belgaum (Karnataka) is used. This fabric is cut into layers of dimensions 300 mm × 300 mm in required orientation. Then all the layers of jute fabric are heated in an oven at 70°C for five to ten minutes to remove the moisture present. The jute stack thickness to form the thin skin on either side of FG core is computed. This enables one to arrive at the required number of fabric layers to be used. With this background data on hand to begin with, the required fabric pieces are dipped in mixture of epoxy and K-6 hardener and placed on base plate forming the bottom stack of the sandwich. FG cores prepared by earlier mentioned procedure are dipped in resin mixture and placed on the bottom stack of skins. Finally, over such an arrangement, the remaining layers of jute fabrics having undergone the same procedure of fabrication are stacked to constitute the top stack of skins. A procedure of this nature should help in ensuring a greater degree of spread of the resin on the fibrillar jute. Following this, the excess resin is made to come out by squeezing operation that is aided by tightening of top plate of the mould. The mould assembly is then cured at room temperature for about 24–26 hours. The sandwich sample is withdrawn from the mould (Figure 1) and trimmed to the required size. Similarly, number of samples is made with various core thickness and skin orientations as schematically illustrated in Figure 2. Table 2 presents sample coding used for sandwich samples.

Figure 1 Mould used for casting sandwich samples (see online version for colours)

Figure 2 Geometrical parameters of sandwich

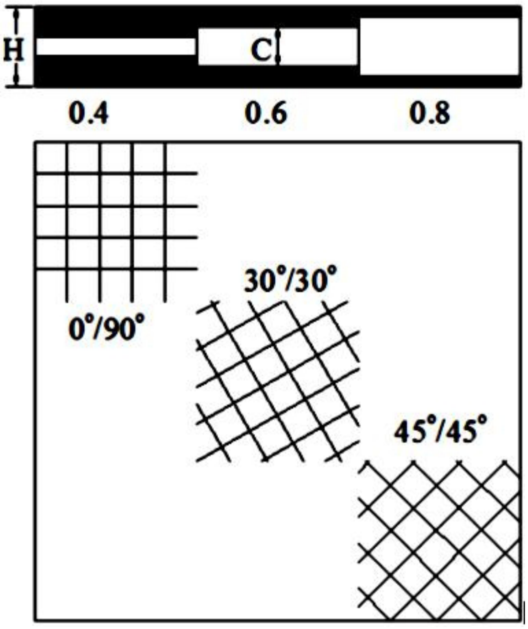


Table 2 Sample coding for sandwich specimens

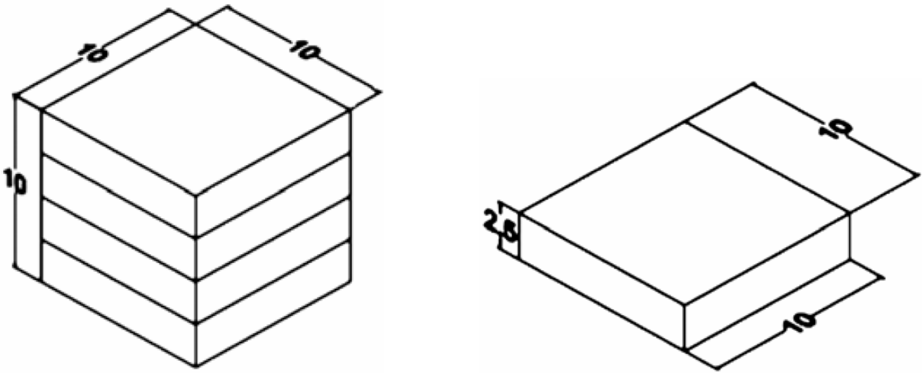
Sample code	*Description*
$W_aO_bR_c$	Sandwich specification
W	Indicates factor 1 (weight % of fly ash)
a	Levels of factor 1 in % (20, 30, 40)
O	Indicates factor 2 (jute skin orientation)
b	Levels of factor 2 (0°/90°, 30°/60°, 45°/45°)
R	Indicates factor 3 (C/H ratio)
c	Levels of factor 3 (0.4, 0.6, 0.8)

2.4 Gradation characterisation of fly ash content

Presence of gradation in prepared cores is established by cutting a test slab of 10 mm × 10 mm × 10 mm [Figure 3(a)]. This is further cut into four thinner slices of dimensions 10 mm × 10 mm × 2.5 mm [Figure 3(b)]. Another casting of rubber but without fly ash and having identical measurement to the filled case is made and sliced for recording weights to establish the filler content. The weight % of fly ash in each slice can be estimated by,

$$\begin{array}{l}\text{% weight}\\ \text{of fly ash}\end{array} = \frac{\text{FG slice weight (gm)} - \text{slice weight of pure rubber (gm)}}{\text{Weight of FG core slice (gm)}} \times 100 \tag{1}$$

Figure 3 (a) FGM sample (b) slice cut from sample



(a) (b)

2.5 Density characterisation for sandwiches

Density is a fundamental physical property that can be used in conjunction with other properties to characterise the material. Density is estimated through experimental route using formula as outlined in ASTM D792 (2008) which is given by,

$$\rho = \frac{W_a}{W_q + W_w + W_b}(\rho_{water}) \tag{2}$$

where ρ = density of the composite material (g/cm^3), W_a = weight of the specimen when hung in air (gm), W_w = weight of the partly immersed wire holding the specimen (gm), W_b = weight of the specimen when immersed fully in distilled water along with the wire holding the specimen (gm) and ρ_{water} is the density in g/cm^3 of the distilled water at testing temperature.

2.6 Testing for ballistic impact behaviour

Ballistic test is carried out on sandwich samples of size 300 mm × 300 mm × 10 mm at National Cadet Corps firing range near Surathkal, Karnataka, India. Mounting arrangement is shown in Figure 4. Manual feed spring operated 0.22 riffle is used for the test. Figure 5 presents schematic of the test setup. Table 3 lists specifications of bullet and the riffle. Bullet used for testing is presented in Figure 6.

Figure 4 Mounting arrangement of specimen (see online version for colours)

Figure 5 Schematic diagram of ballistic testing

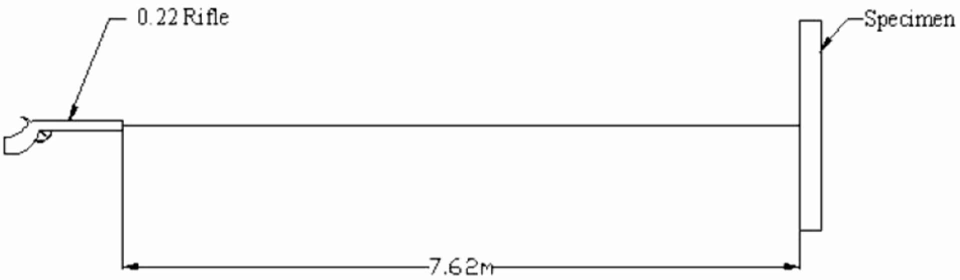
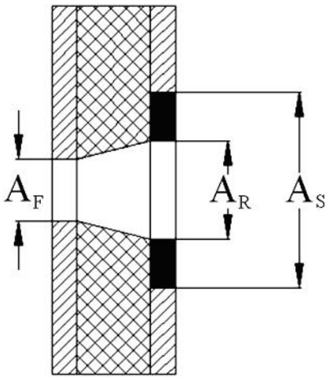


Table 3 Bullet and riffle specifications

Bullet		*Riffle*	
Length	25 mm	Total length	1,100 mm
Diameter	5.62 mm	Barrel length	647.7 mm
Weight	2.6 gm	Weight	2.72 kg
Energy	141 J	Range	25 m
Muzzle velocity	330 m/s	Firing distance	7.62 m

Figure 6 Bullet used for testing (see online version for colours)

Figure 7 Terminology associated ballistic test



The ratios A_R/A_F and A_S/A_R are indicative of the energy absorbed during the travel of bullet from front to rear and energy available in the bullet for skin pullout respectively. Figure 7 shows the schematic of hole generated and the associated terminology.

3 Results and discussion

3.1 Gradation characterisation

Figure 8 presents results obtained from experimental test for gradation characterisation. Values in the bracket represent expected weight % of ash in samples of 20%, 30% and 40% filler content. As seen from Figure 8, distribution of fly ash in different slices clearly validates the presence of gradation of fly ash along the thickness in core samples. Average density of sandwich samples are experimentally estimated using equation (2) are presented in Table 4.

Figure 8 Distribution of fly ash in different slices of FG core (wt %)

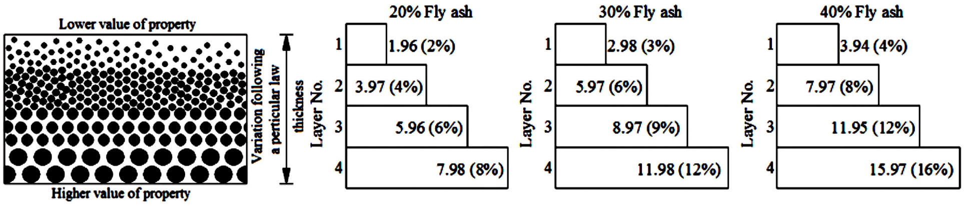


Table 4 Sandwich densities

Sandwich code	*Density (kg/m^3)*
$W_{20}O_0R_{0.4}$	1,329.5
$W_{20}O_{30}R_{0.6}$	1,334.5
$W_{20}O_{45}R_{0.8}$	1,347.3
$W_{30}O_0R_{0.6}$	1,464.82
$W_{30}O_{30}R_{0.8}$	1,456.99
$W_{30}O_{45}R_{0.4}$	1,438.23
$W_{40}O_0R_{0.8}$	1,586.76
$W_{40}O_{30}R_{0.4}$	1,561.11
$W_{40}O_{45}R_{0.6}$	1,560.17

3.2 Ballistic response

The plan of tests is developed with the aim of relating the W, O and R with A_R/A_F and A_S/A_R. On conducting the experiments as per OA, average results for various combinations of parameters are obtained (Table 5).

Table 5 Experimental design and results using L9 OA for A_R/A_F and A_S/A_R

Test	*W (%)*	*O (°)*	*R*	*A_R/A_F (average)*	*A_S/A_R (average)*
1	20	0	0.4	4.239	4.602
2	20	30	0.6	3.033	4.254
3	20	45	0.8	2.438	2.939
4	30	0	0.6	2.69	3.017
5	30	30	0.8	2.138	2.518
6	30	45	0.4	4.35	4.412
7	40	0	0.8	1.405	1.517
8	40	30	0.4	3.499	3.437
9	40	45	0.6	2.998	3.047

3.2.1 Main effects plots

Figure 9 presents graphically the effect of the three control factors on A_R/A_F. Analysis of these plots leads to the conclusion that factor combination of W3, O1 and R3 gives minimum A_R/A_F yielding to higher energy absorption of bullet. Similar observations are made in case of A_S/A_R for W3, O1 and R3 showing lower availability of energy in bullet for skin pullout.

3.2.2 ANOVA

The use of ANOVA is to analyse the influence of material and geometrical parameters on energy absorption and energy availability in skin pullout. This analysis is carried out for a level of significance of 5%, i.e., the level of confidence 95% (Ross, 1995; Roy, 1990). Table 6 shows the results of ANOVA analysis for A_R/A_F while results of A_S/A_R are presented in Table 7. The last column (P) in these tables indicates the probability of significance of control factors. Smaller the value, higher would be the percentage contribution of the factor on the total variation indicating higher degree of influence on the results.

Figure 9 Mean effects plot for A_R/A_F (see online version for colours)

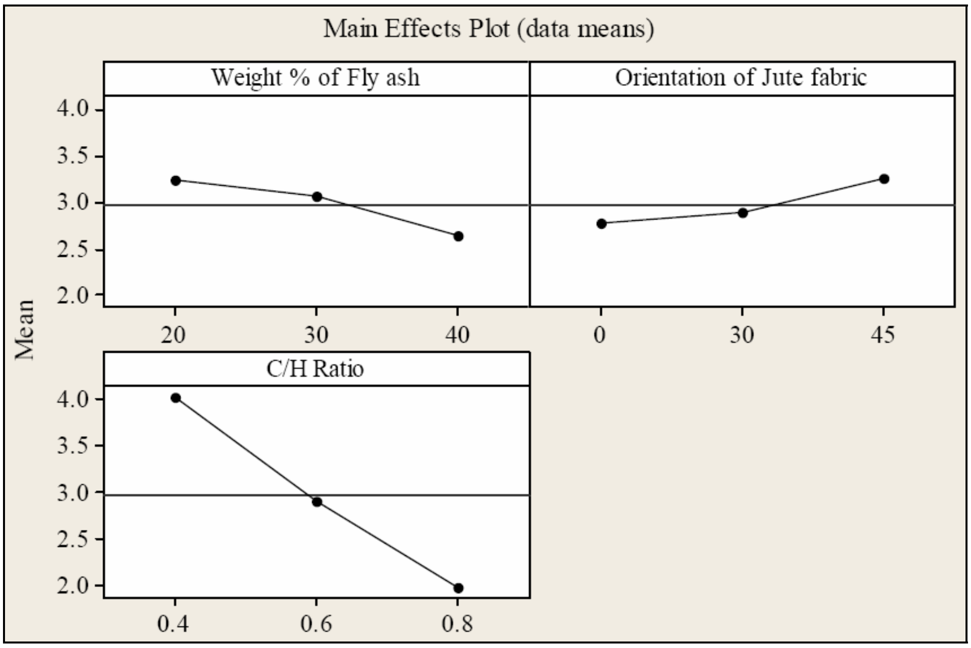


Table 6 ANOVA table for A_R/A_F

Source	*DF*	*SS*	*MS*	*F*	*P*
C/H ratio	2	6.23775	3.11887	25.54	0.005
Weight % of fly	2	0.57556	0.28778	2.36	0.211
Orientation of jute	2	0.39	0.19	0.17	0.85
Error	6	6.92	1.15	---	---
Total	8	7.30183	---	---	---

One can observe from the Table 6 that, the C/H ratio (P = 0.005), fly ash weight fraction (P = 0.211) and jute skin orientation (P = 0.85) are significant in declining order of significance on impact energy absorption. Among the control factors, C/H ratio (P = 0.005) show significance of contribution on A_R/A_F. Jute skin orientation (P = 0.85) is having comparatively less significant contribution indicating that there is an decrease in energy absorption with increase in jute skin orientation. This might be because of the weakening effect resulting in lower strength of skins at higher orientations.

Table 7 ANOVA table for A_S/A_R

Source	*DF*	*SS*	*MS*	*F*	*P*
C/H ratio	2	5.08106	2.54053	22.85	0.006
Weight % of fly	2	2.39961	1.19980	10.79	0.024
Orientation of jute	2	0.31	0.15	0.12	0.888
Error	6	7.62	1.27	---	---
Total	8	7.93	---	---	---

From Table 7, it is clear that C/H ratio (P = 0.006) is having great influence on energy availability in skin pullout. Even though jute skin orientation is the least contributing factor in both cases it cannot be neglected in developing a multiple regression model as it is one of the major load bearing element in sandwich structures.

3.2.3 Surface plots

For both the properties under study, it is clear that C/H ratio and weight fraction of fly ash is having more contribution compared to jute orientation (Table 6 and Table 7). Detailed diagrams in the form of surface plots are presented Figures 10 and 11. Figure 10 depicts that for lower amounts of filler addition not an appreciable decrease in A_R/A_F is observed. Same inference can be drawn even at higher C/H ratio. Lower value of A_R/A_F is observed at higher amounts of control factors resulting in higher impact resistance. AR/AF decreases with increase in fly ash weight fraction and C/H ratio. This might be because of the fact that, with increase in both control factors energy absorption increases due to filler addition with increased penetration area for bullets. Energy availability in skin pullout decreases with increase in controllable factors (Figure 11). Lowest energy in skin pullout is reported at 40% filler addition and 0.8 C/H ratio. This is attributed towards toughening effect due to fly ash reinforcement in thicker cores which gets augmented by presence of gradation in prepared samples.

Figure 10 Surface plot for A_R/A_F (see online version for colours)

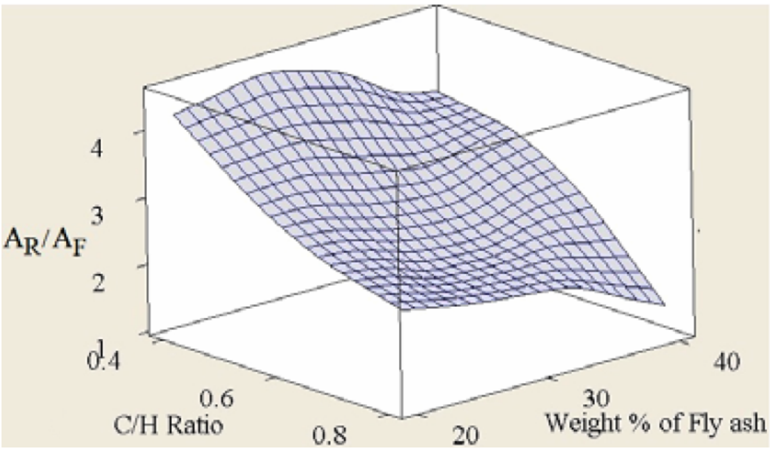
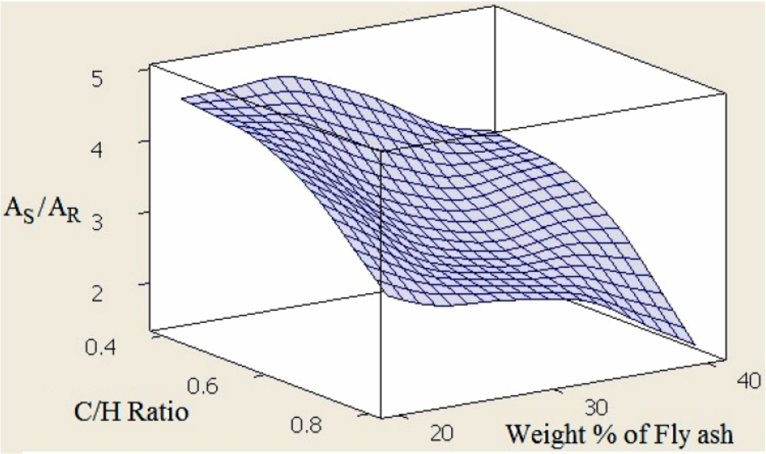


Figure 11 Surface plot for A_S/A_R (see online version for colours)



3.2.4 Regression model

To establish the correlation between ‘W’, ‘O’ and ‘R’ regression model is obtained (Montgomery, 2001) using statistical software (MINITAB 14). All the terms are included in the model. The regression equation for energy absorption (A_R/A_F) is given by,

$$A_R/A_F = 6.69 - 0.0301\ W + 0.00975\ O - 5.09\ R \tag{3}$$

Energy availability in bullet for skin pullout (A_S/A_R) can be estimated as,

$$A_S/A_R = 7.70 - 0.0632\ W + 0.00972\ O - 4.56\ R \tag{4}$$

By substituting the recorded values of the variables for equations (3) and (4), A_R/A_F and A_S/A_R can be calculated. The positive value of the coefficients suggests increase while decrease in shown by negative sign for both the ratios. The important factor affecting the A_R/A_F is the ‘R’ (Table 6) and the coefficient associated with it is negative. This suggests that the A_R/A_F decreases with increasing the ‘R’ for the tested range. Similar observation is made for ‘W’. The coefficient for the remaining factor is observed to be positive indicating increase in A_R/A_F with increasing ‘O’. Main effects plot augments these observations. The decrease in A_R/A_F with increase in ‘W’ and ‘R’ is attributed towards increasing stiffness as ash content increases. With more and more amount of filler in thickness direction (along the bullet impact axis) at higher % of reinforcement available energy in bullet is progressively cut down because of graded cores. Similar readings are observed for energy availability in skin pullout. For both the cases orientation of skins contributed negatively suggesting decrease and increase in energy absorption as well as in available energy in bullet for skin pullout. This might be because of weaker jute strength at higher orientation. The confirmation tests are performed by selecting the set of parameters as shown in Table 8. For these selected parameters experiments are conducted with five replicates. Table 9 presents the comparison of energy absorbed and energy availability in skin pullout results from the regression model developed in the present work [equations (3) and (4)], with the experimentally available values.

Table 8 Parameters used in confirmation tests

Test	*Fly ash weight %*	*Orientation of jute fabric*	*C/H ratio*
1	15	0°	0.3
2	25	30°	0.5
3	35	45°	0.7

Table 9 Confirmation tests and their comparison with regression model

Test	*A_R/A_F*			*A_S/A_R*		
	Experimental	*Regression model (equation 3)*	*% error*	*Experimental*	*Regression model (equation 4)*	*% error*
1	4.912	4.7115	4.08	5.554	5.384	3.06
2	4.126	3.685	10.69	4.369	4.1316	5.43
3	2.751	2.5123	8.68	2.849	2.7334	4.06

From the analysis of the referred table, we can observe that the error between experimental and regression model varies from 4% to 11% and 3% to 6% for A_R/A_F and A_S/A_R respectively. This indicates that the model derived above correlate the ratios in the FG sandwiches with the good degree of approximation.

3.3 Stack thickness optimisation for bullet stoppage

Attempt is made to find optimum thickness of multiple stacked sandwiches (Figure 12) of $W_{40}O_0R_{0.8}$ configuration that can arrest the bullet successfully. Table 10 presents the parameters considered for experimentation. Table 11 presents average values of A_R/A_F for $W_{40}O_0R_{0.8}$ configuration with different sandwich thicknesses. Figure 13 presents a plot of energy absorption by stack of sandwiches.

Figure 12 Typical stack of sandwich used for thickness optimisation (see online version for colours)

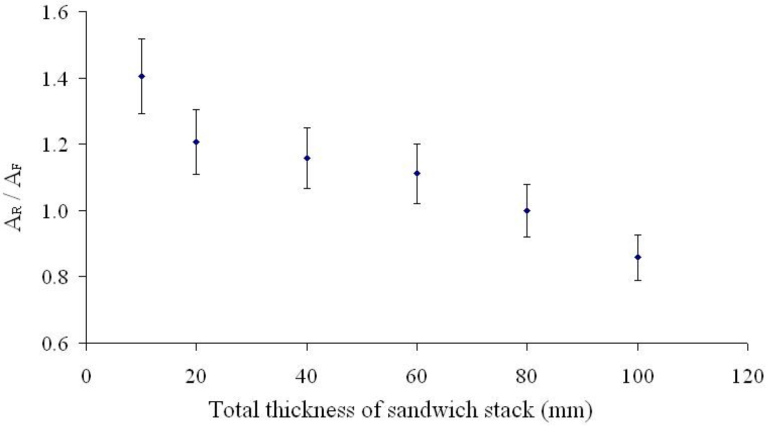
Table 10 Parameters for thickness optimisation

No.	*Sandwich configuration*	*Number of sandwiches*	*Total thickness of stack (mm)*
1	$W_{40}O_0R_{0.8}$	2	20
2		4	40
3		6	60
4		8	80
5		10	100

Table 11 Ballistic impact test results for $W_{40}O_0R_{0.8}$

Sr. no.	*Sandwich configuration*	*Number of sandwiches*	*Total thickness of stack (mm)*	A_R/A_F	*Avg.* A_R/A_F
1	$W_{40}O_0R_{0.8}$	1	10	1.395	1.405
				1.405	
				1.415	
				1.404	
				1.405	
2		2	20	1.201	1.207
				1.211	
				1.206	
				1.228	
				1.188	
3		4	40	1.158	1.158
				1.166	
				1.165	
				1.144	
				1.158	
4		6	60	1.119	1.111
				1.125	
				1.102	
				1.108	
				1.101	
5		8	80	0.998	0.999
				0.889	
				1.009	
				1.1	
				0.999	
6		10	100	0.799	0.859
				0.879	
				0.851	
				0.884	
				0.881	
7		12	120	-----	-----
8		14	140	-----	-----

Figure 13 Energy absorption vs. stack thickness of sandwiches (see online version for colours)



From Figure 13, it is observed that ten sandwiches (100 mm) of $W_{40}O_0R_{0.8}$ can effectively stop the bullet. Sandwiches of 12 and 14 stacks did not show any failure thereby can serve as a potential application at the security posts. Sand bags used in security posts (Figure 14) can be replaced with lighter and stronger sandwich walls (Figure 15) with the wall (stack) thickness of 120 mm.

Figure 14 Usage of sand bags for guarding security posts (see online version for colours)

Figure 15 Sandwich structure as a replacement for sand bags (see online version for colours)

3.4 Ballistic inspection and failure analysis

During the ballistic testing, at least five firings were made to the plates and among the touching points of the bullets, at least 4 diameters distance of a bullet and 2 diameters distance are retained from the edges of the plates. Figure 16 presents a close up view of fractured jute skin and damaged core. In Figure 17, the front and back face of the FG sandwich is shown. Generally, a hole is occurred due to impacting of a bullet. The trace diameters and depth on the back face are displayed in Figure 17.

Figure 16 Fractured sample (see online version for colours)

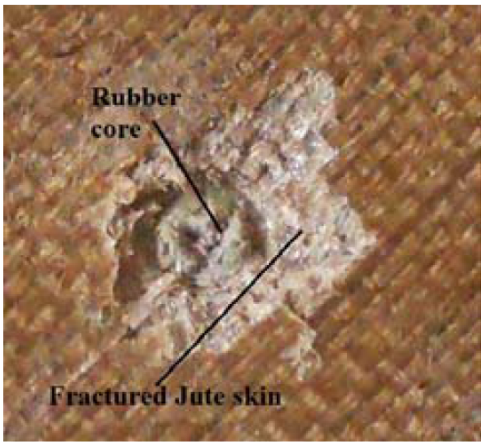


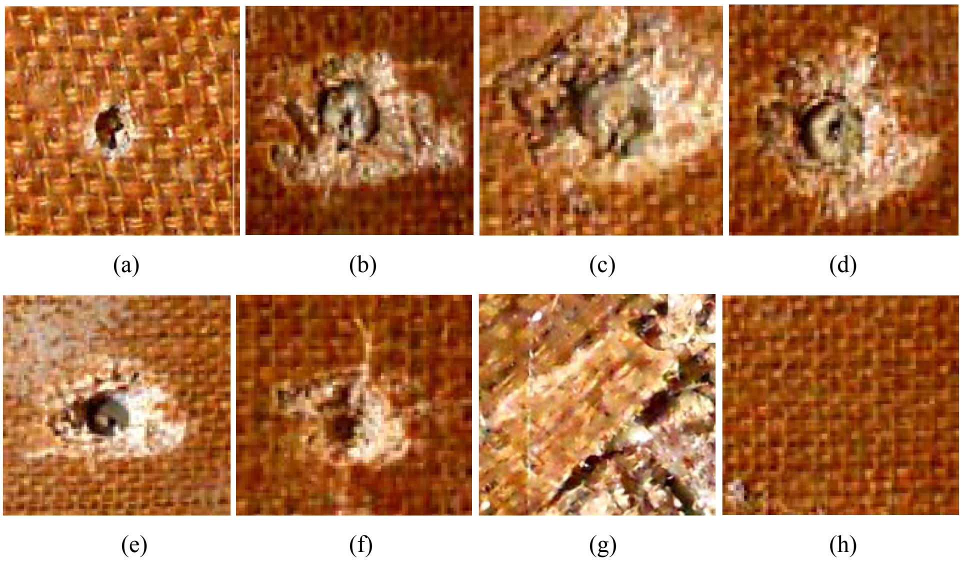
Figure 17 Demonstration of (a) front and (b) back face (see online version for colours)

(a) (b)

Figure 18 presents fractured areas at the rear side in the sandwich stack of $W_{40}O_0R_{0.8}$ used for stack thickness optimisation.

It is seen from Figure 18 that the depth of trace of bullets decreased with the increment of sandwiches. This means that the protected person survives all speeds of bullet (about 350 m/s) if 12 layers of sandwiches are used.

Figure 18 Surface at the rear end [(b) to (h)] as a function of total sandwich thickness in the stack, (a) front side (b) 10 mm (c) 20 mm (d) 40 mm (e) 60 mm (f) 80 mm (g) 100 mm (h) 120 mm (see online version for colours)



4 Conclusions

1 Presence of gradation in core is quantified through weight method.

2 An optimal parameter combination registering highest energy absorption happens to be $W_{40}O_0R_{0.8}$. Energy absorption increases with weight fraction of C/H ratio (most significant factor) and fly ash.

3 The residual errors associated with the ANOVA are observed to be lower for the factors and the coefficient of regression obtained with the multiple regression values show that the satisfactory correlation is obtained.

4 The confirmation tests showed that error associated with energy absorption in FG sandwiches is well within 11%.

5 The depth of trace of the bullet is decreased with the increment of sandwich layer numbers. Protected person survives all speeds of bullet (up to 350 m/s) if 12 layers of $W_{40}O_0R_{0.8}$ are used.

6 $W_{40}O_0R_{0.8}$ with 12 layers (120 mm) constituting the sandwich wall could be the best proposition as a replacement for heavy sand bags used for guarding military posts.

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