Behavioral Study and Evaluation of Rubber Core Sandwich Beam Under Impact Loading

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Abstract:- The shock resistance of structures is of current interest of academia and industry. Sandwich structures have been proposed as alternatives to conventional monolithic structures in order to enhance the shock resistance. Sandwich structures are widely used in many important fields, such as ship, aircraft, automotive and aerospace industries, packaging and construction engineering.

In this study, a number of experiments were conducted to investigate the structural response of dynamically loaded on clamped (both end) 1mm thick monolithic aluminium beams and rubber core sandwich beams of 3.02 mm and 4.02 mm thicknesses impacted by a blunt nosed cylindrical projectile made of mild steel of diameter 12.8 mm, length 30.2 mm and mass 0.03018 Kg in sub ordinance velocity range (20 to 110 m/s). Sandwich structure consists of two face sheets of aluminium adhered to a low-density rubber core. The failure of composite specimens observed in the tests can be classified with respect to the front face sheet, core and back face sheet, respectively Different parameters like impact velocity, residual velocity, velocity drop, energy absorbed, kinetic energy, deflection, dimensionless external dynamic energy, and dimensionless maximum transverse permanent deformation were observed experimentally and calculated analytically with the help of work in the past.

Three modes of failure of beams have been found during the experiment on monolithic and rubber core sandwich beams like mode-1: Fracture at the point of strike i.e. tearing; mode-2: Fracture at one or both support either on front face sheet or on back face sheet of beam i.e. end shear; mode-3: Fracture at the point of strike with bulging (cup shape) and after fracture beam turnaround from the support (in case of monolithic) or Fracture at the point of strike without bulging on front face sheet and after fracture on the back face sheet with bulging and beam turnaround from the support (in case of sandwich beam).

Keywords:- *Sandwich Beam, Sandwich Material, Light Weight Structure, ANSYS.*

I. INTRODUCTION

Beam systems and frames made of more than one material are often used in the building system for use the advantage of different materials in the composite. As an example the reinforced concrete structure is made up of two parts the main materials have a specific function, the concrete is very good at pressure but does poorly when it is heated over time steel can withstand strong forces that can produce bending in the system. The installation of the integrated item must consider working with a combination.

Understanding material's behaviour when subjected to impact loading is important forgaining a better understanding of impact problem & developing design tools. The high strain rates associated with impact loading affect both flow stress & material's ductility. The beam, or flexural member, is a common structural and machine component, and its basic stress analysis is one of the more intriguing facts of material mechanics.

The intensity of impact could be as small as the hit of a droplet of rainwater on earth& as high as collision of two heavenly bodies such as comets or asteroids. It is also believed that origin of universe & evolution of life is a result of impact. Previously, impact issues weremostly reserved for military. As civilian technology progresses, more study is being performed to better understand behaviour of materials subjected to short-term loading. Engineers interested in impact dynamics include those working on lightweight body armour design, the safety of nuclear-reactor containment containers when hit by a missile or an aircraft, spacecraft protection from meteoroid impact, safe demolition of pre-stressed concrete structures, & transportation safety of hazardous materials.

II. IMPACT OF PROJECTILE ON TARGETS

The investigation of structural failure under impact loading is critical for assessing structural safety & hazards. When subjected to dynamic loading, simple structural elements such as beams, plates, and shells fail in a variety of ways. Scientists & engineers have paid more attention to beams because they are relatively critical elements. During September 11th attack, two planes travelling at 264 m/s (590 mph) & 210 mps (470 m/h) collided with South and North Towers of World Trade Center. The Twin Towers collapsed as a result of the damage sustained during the impact processes. Within milliseconds of events, the exterior columns were cut through by aeroplane wings, as shown in Fig. 1

Fig 1:- A “a "clean" cut driven into the North Tower's facade by the wings of a Boeing 767

The study of the impact of projectiles on targets has a nearly two-and-a-half-century history. The first 150 years were devoted to empirical studies of the degree of penetration or perforation of numerous targets stuck in a variety of conditions by various missiles at a variety of initial velocities.

Simple semi-empirical or quasi-rational representations of impact emerged at the end of the nineteenth century. Various mechanisms manifested themselves in these collisions, providing a measure of predictive capability. Various mechanisms manifested in these collisions and thus provide a measure of predictive capability; these have been successively refined throughout the twentieth century to provide a more precise model.

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Understanding how structural elements behave when subjected to impact loads that induce substantial inelastic deformations failure is crucial. Engineers & designers in several sectors must calculate the maximum amount of energy that a specific deformation can absorb.Passenger car deformations, for example, are intended to maintain a survivable volume with acceleration levels that minimize human harm in a range of collision situations. In other words, greatest amount of energy that can be absorbed prior to a material breakdown is necessary in practice. This data would be required, for example, to assess the structural integrity of LNG tankers involved in a collision. Many other safety calculations and hazard assessments involving impact, dynamic pressure, or explosive loads would need the use of structural impact data.

The impact phenomenon founds **application** in following fields:

- Projectile impact on amour.
- The transportation of hazardous materials in a safe manner.
- Nuclear reactor containment vessel safety.
- Military vehicles, aircraft, and structures are designed to withstand impact andexplosive loading.
- Protection of spacecraft from meteoroid impact.
- Design of lightweight body amours for executive, government and military personnel.

There is a need for safer structures that can absorb impact energy while also being resistantto penetration and perforation. The safe & cost-effective design of structures subjected to impact loading necessitates a thorough understanding of the material's behaviour. Production engineers, for example, are interested in subject because of its application to high speed blanking and hole flanging processes; military scientists need to understand subject in order to design structures that are most efficient, such as understanding projectile impact or designing improved ballistic missiles; and vehicle manufacturers use their understanding of structural response to impact loading to improve performance & safety of their product. Furthermore, impact dynamics aid geologists in their understanding of the planet.

A. *Striker and projectile*

Any object that causes an impact is referred to as a striker; projectiles are devices that provide specific ballistic performance; and penetrators are objects that achieve terminalballistic goals. A projectile can be anything that can be launched.

The projectiles can be characterized by their geometry, material, speed and trajectory [1]. Projectile weight may vary from hundreds of kilogram (as in the case of failed turbine blade) to fractions of a gram (as in the case of secondary small particles resulting from a high velocity impact). The projectile may consist of a single material or combination1of materials.A projectile may emerge undamaged, plastically deformed, fractured or shattered as a resultof its encounter with the target. The performance of the projectile depends on its nose shape, its length to diameter ratio, material and the velocity of impact.

Military projectiles are probably the most familiar, but, components of failed industrial machinery such as turbine blades and busting of high pressure vessel can result in high speed, irregular missiles that may cause large damage to the structures near it. Large andsmall meteorites have been a hazard to space vehicles. With the increasing interest in use of space for industrial application & basic research, questions of protection of manned and unmanned space vehicles from high -velocity meteorite impact have again arisen.

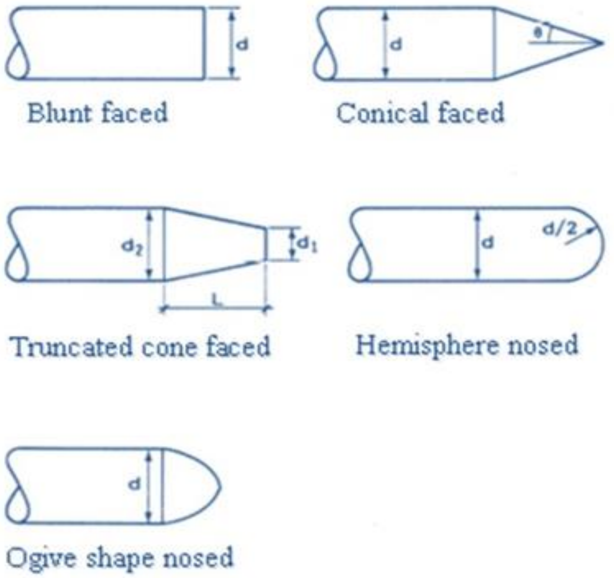

Fig 2 Different shapes of projectile

B. *Sandwich Theory*

Sandwich theory describes behaviour of a three-layer beam, plate, or shell having two face sheets & one core. Sandwich theory, which is an extension of first order beam theory, is most popular. Linear sandwich theory is required for constructing and analysing sandwich panels used in building construction, automotive construction, aircraft construction, and refrigeration engineering.

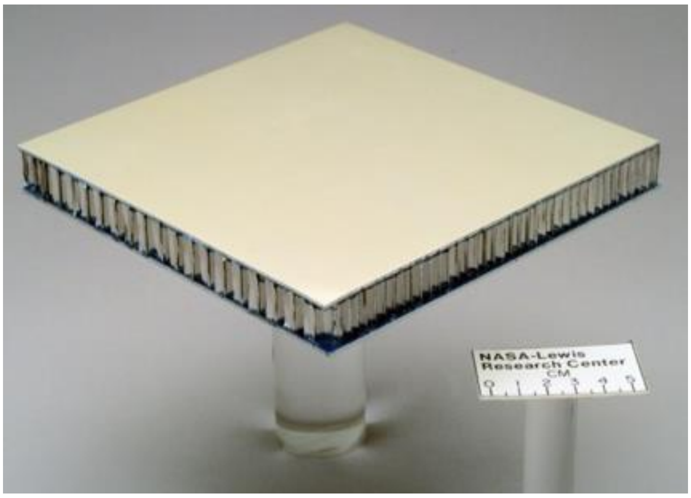

Fig 3 Composite sandwich structure panel used for testing at NASA.

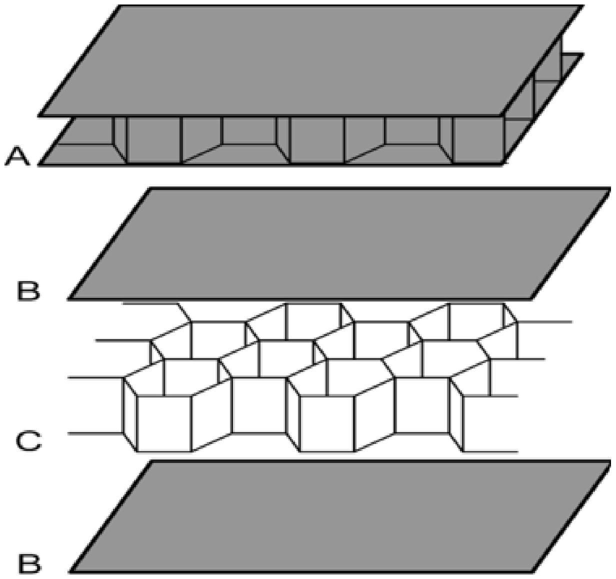

Fig 4:- Diagram of an assembled composite sandwich (A), & its constituent face sheetsor skins (B) & core (C)

C. *Engineering Sandwich Beam theory*

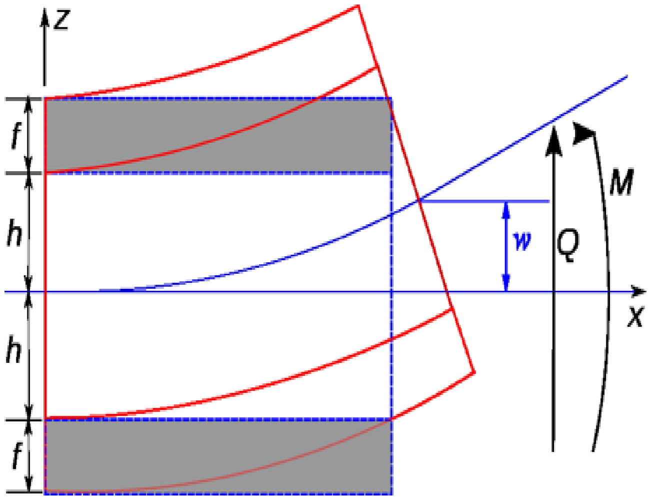

Fig 5 Bending of a sandwich beam with no additional deformation caused by core shear.

The axial strain is assumed to vary linearly across cross-section of beam in engineering theory of sandwich beams [21], as in Euler-Bernoulli theory, i.e.,

$$\varepsilon_{xx}(x,z) = -z\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

As a result, axial stress in sandwich beam is denoted by

$$\sigma_{xx}(x,z) = -z\ E(z)\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

where E(z) is Young's modulus, which varies with location along the beam'sthickness. Then in beam is given by

$$M_x(x) = \int z\ \sigma_{xx}\ \mathrm{d}z = -\left(\int z^2 E(z)\ \mathrm{d}z\right)\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2} = -D\ \frac{\mathrm{d}^2 w}{\mathrm{d}x^2}$$

The quantity *D* is called flexural stiffness of sandwich beam. The shear force Q_x is defined as

$$Q_x = \frac{\mathrm{d}M_x}{\mathrm{d}x}\ .$$

Since

$$\frac{d^2 w}{dx^2} = -\frac{M_x(x)}{D}$$

we can write axial stress as

$$\sigma_{xx}(x,z) = \frac{z\ E(z)\ M_x(x)}{D}$$

The equilibrium equation for a two-dimensional solid is given by

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} = 0$$

where η_{xz} is shear stress. Therefore,

$$\tau_{xz}(x,z) = \int \frac{\partial \sigma_{xx}}{\partial x}\ \mathrm{d}z + C(x) = \int \frac{z\ E(z)}{D}\ \frac{\mathrm{d}M_x}{\mathrm{d}x}\ \mathrm{d}z + C(x)$$

where $C(x)$ is a constant of integration. Therefore,

$$\tau_{xz}(x,z) = \frac{Q_x}{D}\int z\ E(z)\ \mathrm{d}z + C(x)$$

Assume that no shear tractions are applied to the sandwich beam's top face. The shearstress on top face of the sheet is given by

$$\tau_{xz}^{\text{face}}(x,z) = \frac{Q_x E^f}{D}\int_z^{h+f} z\ \mathrm{d}z + C(x) = \frac{Q_x E^f}{2D}\left[(h+f)^2 - z^2\right] + C(x)$$

At $z= h+f$, $\eta_{xz}(0, h+f) =0$ implies that $C(x) =0$. Then shear stress at top of core, $z =h$, isgiven by

$$\tau_{xz}(x,h) = \frac{Q_x E^f f(f+2h)}{2D}$$

Similarly, shear stress in core can be calculated as

$$\tau_{xz}^{\text{core}}(x,z) = \frac{Q_x E^c}{D}\int_z^{h} z\ \mathrm{d}z + C(x) = \frac{Q_x E^c}{2D}\left(h^2 - z^2\right) + C(x)$$

The integration constant $C(x)$ is determined from continuity of shear stress at interface of core & face sheet. Therefore,

$$C(x) = \frac{Q_x E^f f(f+2h)}{2D}$$

&

$$\tau_{xz}^{\text{core}}(x,z) = \frac{Q_x}{2D}\left[E^c\left(h^2 - z^2\right) + E^f f(f+2h)\right]$$

Using these relations, we can show that stresses in a sandwich beam with a core of thickness $2h$ and modulus E^c and two face sheets each of thickness f and modulus E^f, are given by

$$\sigma_{xx}^{\mathrm{f}} = \frac{zE^{\mathrm{f}}M_x}{D}\ ; \qquad \sigma_{xx}^{\mathrm{c}} = \frac{zE^{\mathrm{c}}M_x}{D}$$

$$\tau_{xz}^{\mathrm{f}} = \frac{Q_x E^{\mathrm{f}}}{2D}\left[(h+f)^2 - z^2\right]\ ; \qquad \tau_{xz}^{\mathrm{c}} = \frac{Q_x}{2D}\left[E^{\mathrm{c}}\left(h^2 - z^2\right) + E^{\mathrm{f}} f(f+2h)\right]$$

For a sandwich beam with identical face sheets value of D is

$$\begin{aligned} D &= E^f\int_{-h-f}^{-h} z^2\ \mathrm{d}z + E^c\int_{-h}^{h} z^2\ \mathrm{d}z + E^f\int_{h}^{h+f} z^2\ \mathrm{d}z \\ &= \frac{2}{3}E^f f^3 + \frac{2}{3}E^c h^3 + 2E^f fh(f+h)\ . \end{aligned}$$

If $E^f \gg E^c$, then D can be approximated as

$$D \approx \frac{2}{3}E^f f^3 + 2E^f fh(f+h) = fE^f\left(\frac{2}{3}f^2 + h(f+h)\right)$$

And stresses invsandwich beam can be approximated as

$$\sigma_{xx}^{\mathrm{f}} \approx \frac{zM_x}{\frac{2}{3}f^3 + 2fh(f+h)} ; \qquad \sigma_{xx}^{\mathrm{c}} \approx 0$$

$$\tau_{xz}^{\mathrm{f}} \approx \frac{Q_x}{\frac{4}{3}f^3 + 4fh(f+h)}\left[(h+f)^2 - z^2\right] ; \qquad \tau_{xz}^{\mathrm{c}} \approx \frac{Q_x(f+2h)}{\frac{2}{3}f^2 + h(f+h)}$$

If, in addition, $f \ll 2h$, then

$$D \approx 2E^f fh(f+h)$$

And approximate stresses in beam are

$$\sigma_{xx}^{\mathrm{f}} \approx \frac{zM_x}{2fh(f+h)} ; \qquad \sigma_{xx}^{\mathrm{c}} \approx 0$$

$$\tau_{xz}^{\mathrm{f}} \approx \frac{Q_x}{4fh(f+h)}\left[(h+f)^2 - z^2\right] ; \qquad \tau_{xz}^{\mathrm{c}} \approx \frac{Q_x(f+2h)}{4h(f+h)} \approx \frac{Q_x}{2h}$$

We have approximation if we assume that facesheets are thin enough that stresses canbe assumed to be constant throughout thickness.

$$\sigma_{xx}^{\mathrm{f}} \approx \pm\frac{M_x}{2fh} ; \qquad \sigma_{xx}^{\mathrm{c}} \approx 0$$

$$\tau_{xz}^{\mathrm{f}} \approx 0 ; \qquad \tau_{xz}^{\mathrm{c}} \approx \frac{Q_x}{2h}$$

As a result, problem can be divided into two parts: one that only involves core shear & otherthat involves bending stresses in face sheets.

III. DETERMINATION OF MATERIAL PROPERTIES

Quasi-static tensile tests were carried out to obtain properties of material. Flat specimens were cut from the aluminium sheets in two different directions (0° and 90°). The load displacement graphs for all three thicknesses are plotted and 0.2% offset yield strength iscalculated.

The load P and deformation δL are obtained from the load-deformation curve. The area is measured using a vernier calliper from the tensile test specimen hence we obtain the value for strain for each stress value and can plot the stress-strain curve. On this curve 0.2 % strain is plotted and extended to find the value of yield strength. The Stress-strain curves for the 3 thicknesses are shown in the Fig. 4.11, 4.12 and 4.13 respectively. The stress strain curves were plotted using the formulae given in Eqn. (4.1) and Eqn. (4.2).

$$\sigma = \frac{P}{A} \qquad (4.1)$$

$$\epsilon = \frac{\delta L}{L} \qquad (4.2)$$

where
ε→ Strainζ→ Stress
L→ Gauge lengthP→ Load
A→ Cross sectional areaδL → Deformation

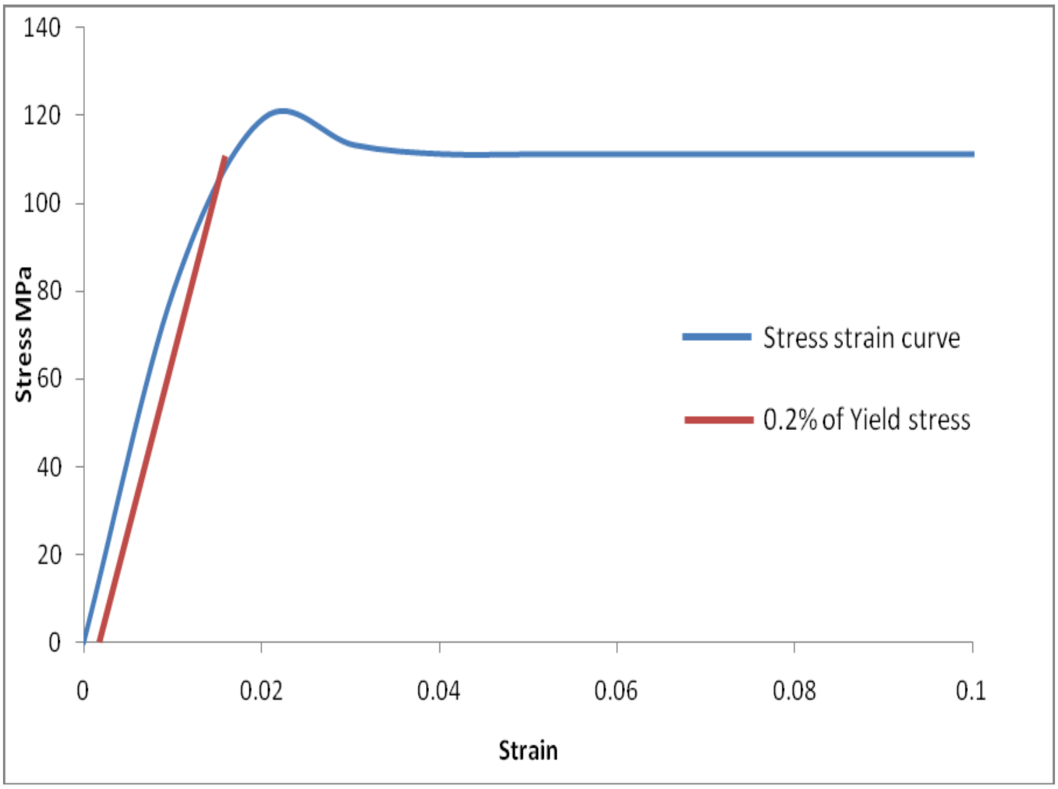

Fig 4.1 Stress strain Curve shown 0.2% offset yield strength for specimen of 1 mm thickaluminium beam

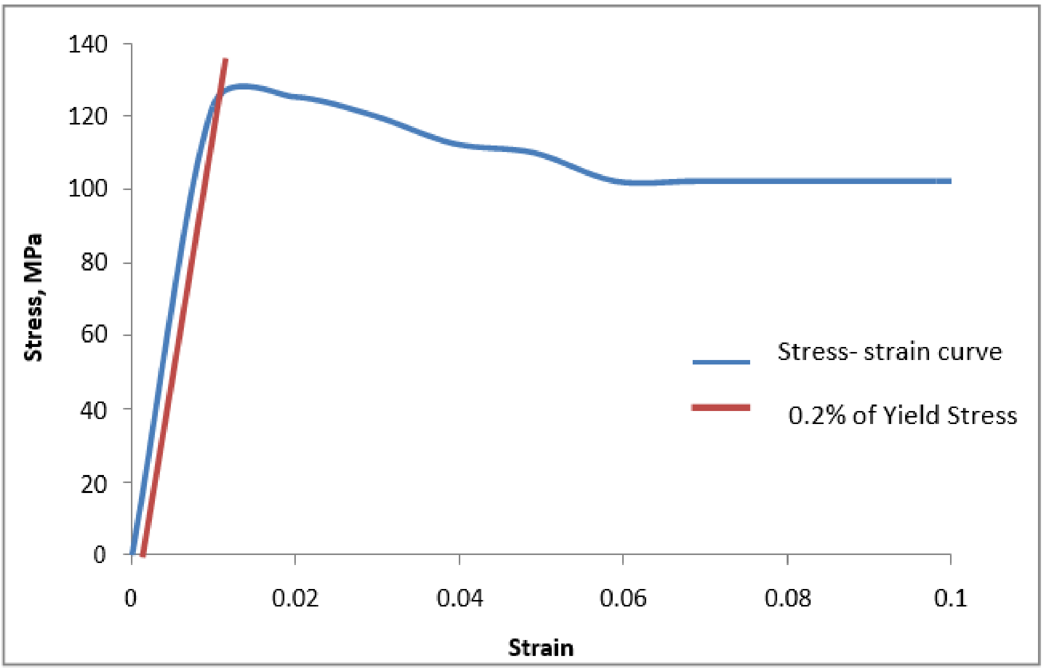

Fig 4.2 Stress strain Curve shown 0.2% offset yield strength for specimen of 3.02 mmrubber core sandwich beam (RA)

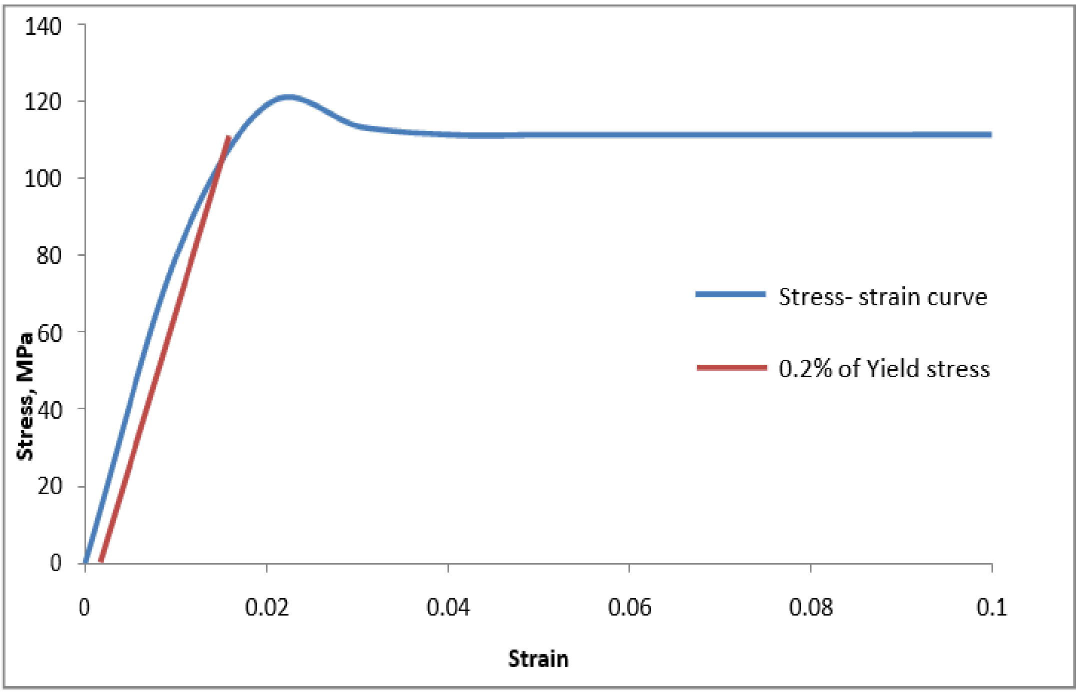

Fig 4.3 Stress strain Curve shown 0.2% offset yield strength for specimen of 4.02 mmrubber core sandwich beam (RB)

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Results of the measurements of the impact and residual velocities, beam deformation and derived values of the velocities drop and the energy absorbed in perforation are presented. Analysis is presented and useful mathematical relations are used to compute residual velocities. Their variations with the impact velocity are discussed. Through a seriesof studies, Forrestal & co-authors [23] developed accurate, closed form equations that predict ballistic limit & residual velocities of the target based on the projectile's nose shape.

According to them the ballistic limit velocity can be written as

$$V_{bl} = \sqrt{\left[2 * \left(\frac{h}{L}\right) * \left(\frac{\sigma_s}{\rho_p}\right)\right]} \qquad (5.5)$$

Where

σ_s is Quasi-static radial stress. E is young's modulus

ρ_p is density of projectile. Y is yield stress

n is strain hardening exponent used to fit stress-strain data.

V_s is the striking velocity

And Quasi-static radial stress is given by

$$\sigma_s = \frac{Y}{\sqrt{3}}\left\{1 + \left[\frac{E}{(\sqrt{3} * Y)}\right] * I^n\right\} \qquad (5.6)$$

where

$$I = \int_0^b \frac{(-\ln x)^n}{(1-x)} dx \ ; \ b = 1 - \frac{(\sqrt{3} * Y)}{E}$$

$$(5.7)$$

The equation for residual velocity is,

$$V_r = V_{bl} * \sqrt{\left[\left({}^{V_s}\!/_{V_{bl}}\right)^2 - 1\right]} \qquad (5.8)$$

➢ *Experiments On Aluminium And Rubber Core Sandwich Beams With Blunt Nosed Projectile*

A number of experiments on aluminium beams of thickness 1mm, rubber core sandwich beams of thicknesses 3.02 mm and 4.02 mm were carried out to study the responseof the beams subjected to impact of a blunt nosed projectile.

➢ *Effect Of Beam Thickness And Impact Velocity*

The measured values of residual velocity are plotted against impact velocity for 1 mm thick aluminium beam and 3.02 mm and 4.02 mm rubber core sandwich beams as shownin Fig. 5.13 & Fig.5.16 respectively. It is sheen that residual velocity increases with increase in impact velocity for each thickness. This increase is more rapid initially and later curveof residual velocity versus impact velocity tends to become parallel to the 45^0 line for 1 mm thick aluminium beam and about 55^0 for rubber core sandwich beams as shown in Fig. 5.13& Fig.5.16 respectively. The residual velocity decreases with increase of beam thickness at the same impact velocity.

The variation of velocity drop with the impact velocity is shown in Fig. 5.14 and Fig.5.17 where it is clear that the velocity drop is more in thicker target beams. It is observed from Fig.5.14 that velocity drop decreases with increase in impact velocity for aluminium beam and it is also observed from Fig. 5.17 that the velocity drop increases with increase in impact velocity upto 60 m/s and above this velocity, velocity drop decreases. Velocity drop isfound to be maximum in 4.02 mm thick rubber core sandwich beam at varying impact velocity and it is found to be minimum in 1 mm thick aluminium beam.

The effect of impact velocity on energy of projectile absorbed by beam during perforation is shown in Fig. 5.15 and Fig. 5.18. The absorbed energy is first increases upto 60 m/s and after that it decreases for aluminium beams is shown in Fig. 5.15 and absorbed energy increases with increase in impact velocity for rubber core sandwich beams as shown in Fig. 5.18. For impact velocities of the projectile above 65 m/s energy absorbed ismore rapid in 4.02 mm rubber core sandwich beams as compare to 3.02 mm rubber core sandwich beams. The absorbed energy increases with increase of beam thickness.

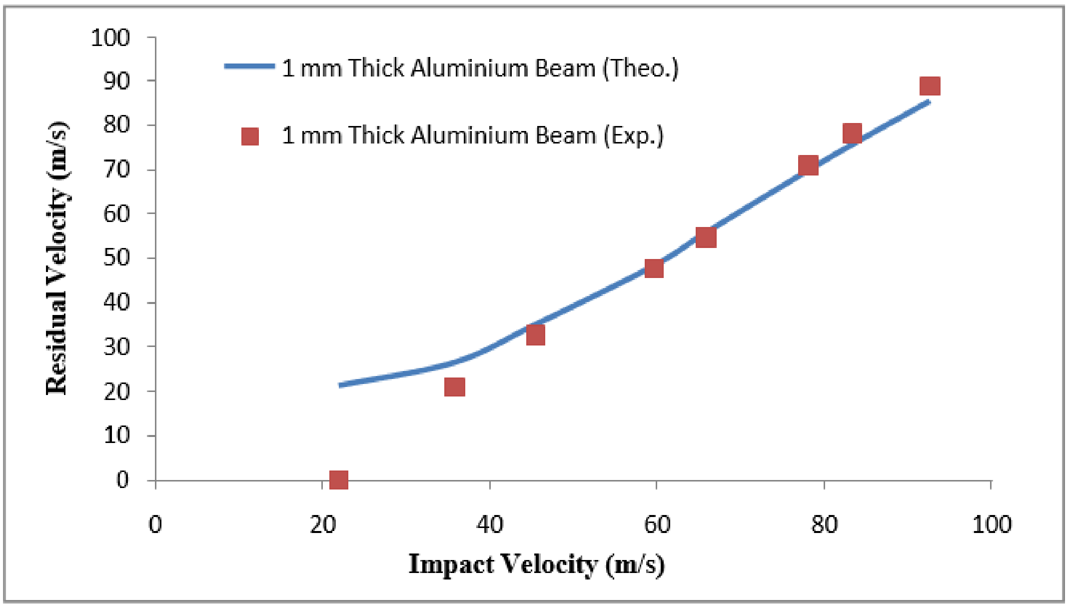

Fig 5.1 Comparison of residual velocity Vs impact velocity for 1mm thick aluminiumbeams of blunt nose projectile

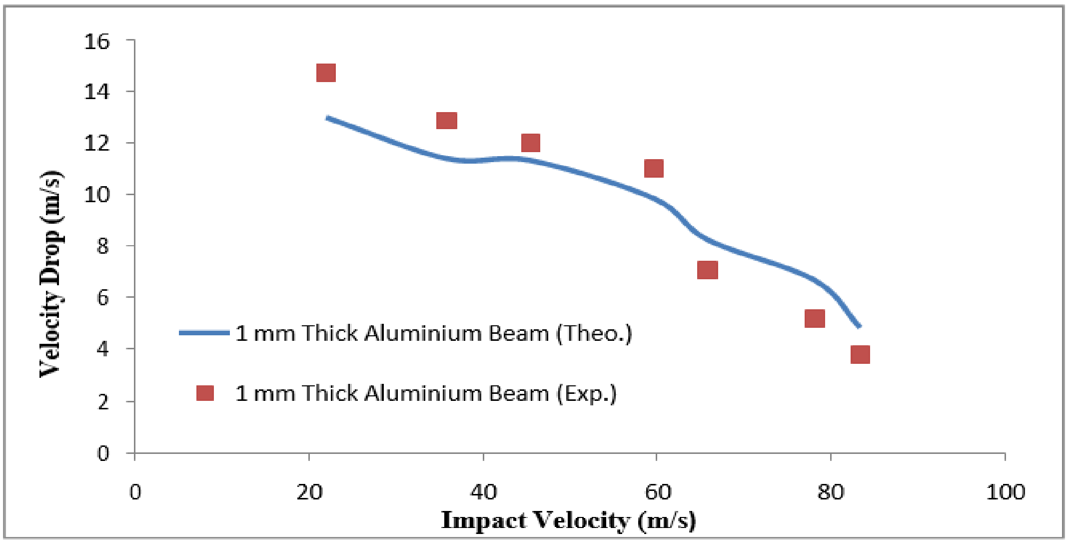

Fig 5.2 Comparison of velocity drop Vs impact velocity for 1mm thick aluminium beamsof blunt nose projectile

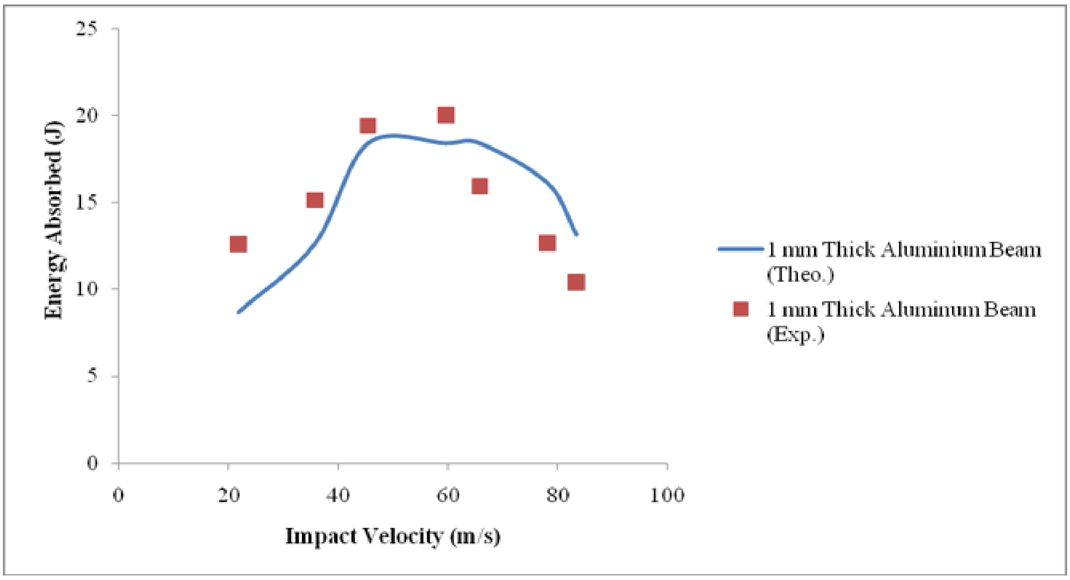

Fig 5.3 Comparison of energy absorbed Vs impact velocity for 1mm thick aluminiumbeams of blunt nose projectile

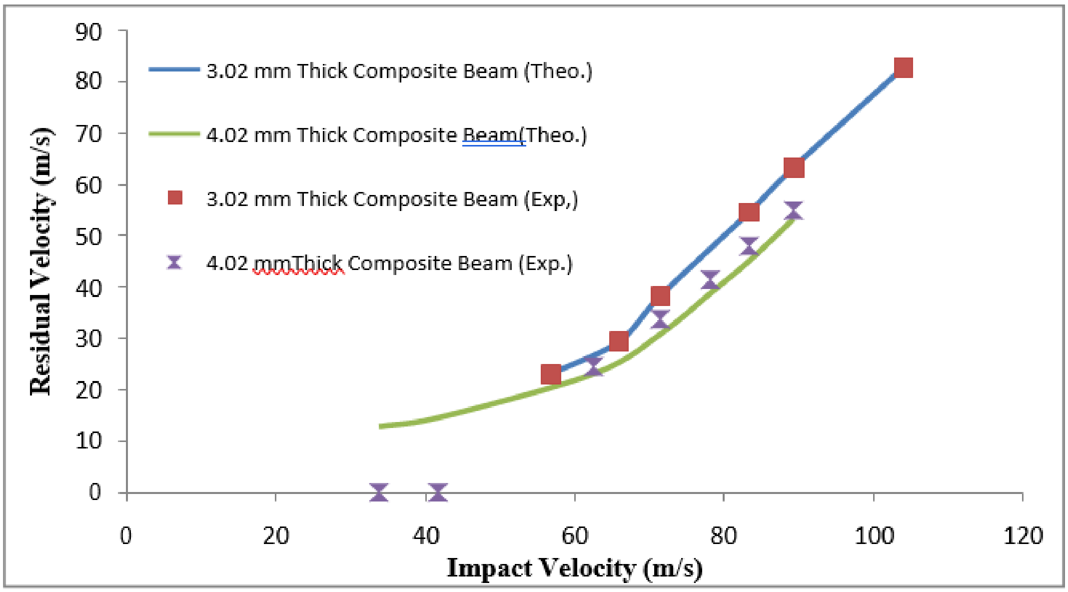

Fig 5.4 Comparison of residual velocity Vs impact velocity for rubber core sandwichbeams of different thicknesses of blunt nose projectile

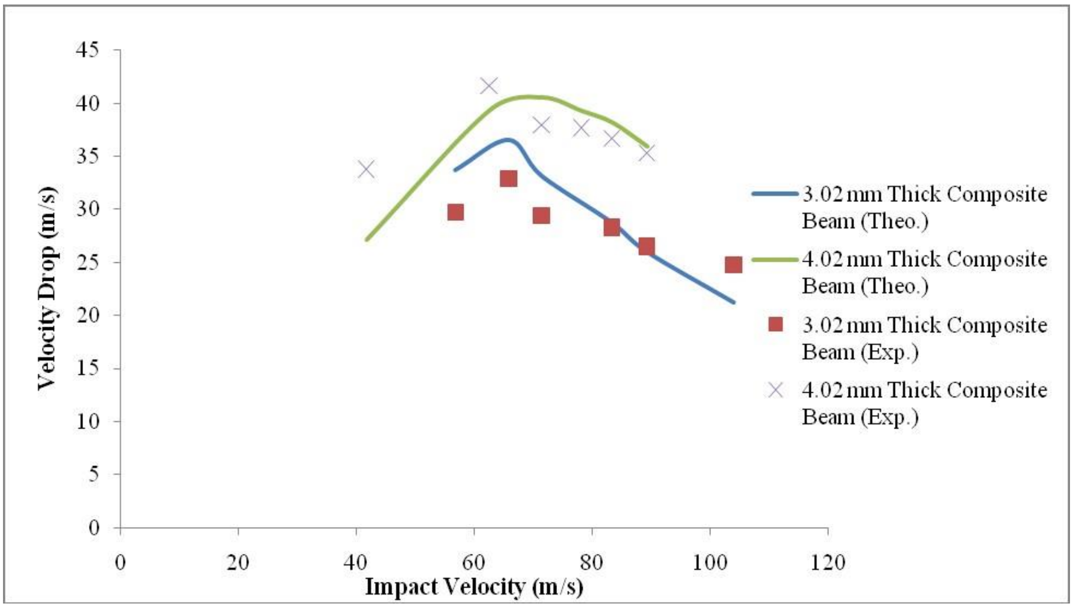

Fig 5.5 Comparison of velocity drop Vs impact velocity for sandwich rubber coresandwich beams of different thicknesses of blunt nose projectile

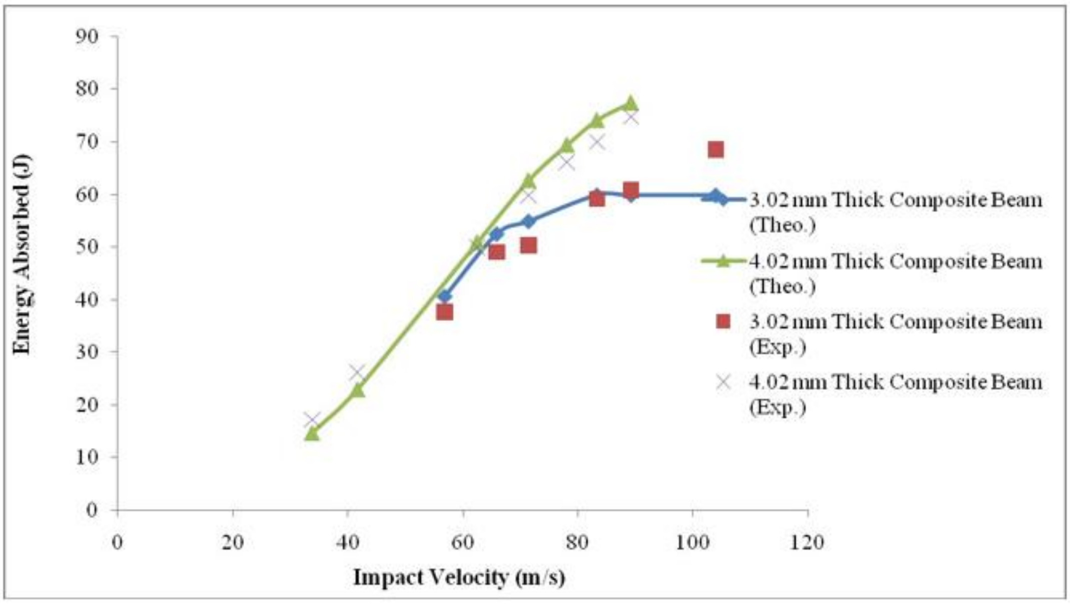

Fig 5.6 Comparison of experimental absorbed energy Vs impact velocity for 4.02 mmrubber core sandwich beams of blunt nose projectile

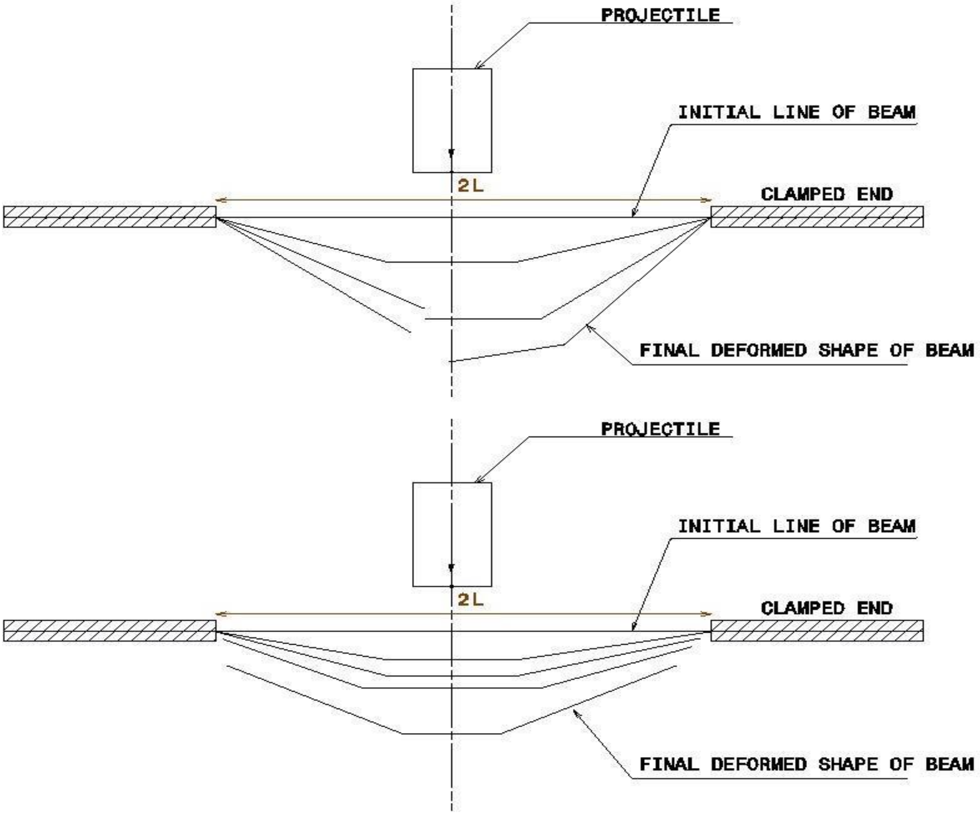

Fig 5.7 (a) Progress of collapse of beam at low velocity by fracture at point of strike &by shear-off at t clamped end for aluminium beam

The % study deals with the experimental investigation on the behavior of clamped (both end) 1 mm thick aluminium beams and rubber core sandwich beams of 3.02 mm, 4.02 mm thicknesses subjected to impact by a blunt nosed cylindrical projectile made of mild steel of diameter 12.8 mm, length 30.2 mm and mass 0.03018 Kg at a velocity in sub ordinance range ($V_0 \approx 20 - 110$ m/s).

- Three modes of failure of beams have been found during the experiment on monolithic and rubber core sandwich beams like - Type 1fracture at point of strike i.e.tearing; Fracture at one or both support i.e. end shear; Fracture at point of strike with or without bulging (cup shape) & after fracture beam turnaround from support.
- The deformation of composite specimens observed in tests can be classified with respect to front face sheet, core and back face sheet, respectively. The deformation infront face sheet is found to be less as compare to back face sheet because core resist the deformation of the front face sheet. The used core is an elastic member so the deformation is very less in core. When a projectile hits the target the rubber absorb theshock provided by the projectile and waves are generated in the rubber, rubbertransmit these waves to back face sheet of sandwich beam due to this severity is foundmore in back face sheet of rubber core sandwich beam.
- Dimensionless maximum permanent transverse deformation and dimensionlessexternal dynamic energy (lamda) increases with increase in impact velocity and the deformation is found maximum in thinnest beam and as the thickness increases the deformation is found less for the same impact velocity.
- In case of thick sandwich beam the projectile leaves deep indentation at point of strike. The indentation is found more deep on front face sheet than back face sheet of rubber core sandwich beams.
- Projectile is impacted normally on the target beams with varying impact velocities. Impact and residual velocities are measured by the digital storage oscilloscope and residual velocity & energy absorbed by beam has been calculated. Residual velocity, velocity drop and energy absorbed by the monolithic sandwich beams impacted by a projectile is related to impact velocity & plate thickness.
- The results are compared value obtain from existing experimental setup and themathematical model proposed by the M.J. Forrestal, T. Børvik. The residual velocity increases with increase in impact velocity. It is found maximum for 1 mm thick aluminum beam and as the thickness increases residual velocity of projectile decreases. The velocity drop decreases with increase in impact velocity for aluminium beam and it is also seen that the velocity drop for rubber core sandwich beams increases with increase in impact velocity upto 60 m/s and above this velocity, velocity drop decreases. Absorbed energy increases with increase in impact velocity for rubber core sandwich beams.

V. SCOPE FOR FUTURE WORK

- The present analysis can also be done for different types of sandwich beams, in whichthe core material may use as light as possible.
- The present analysis can also be done by using projectile of different nose shapes. It isalso suggested to perform experiments to see effects of varying diameter, shank length.
- The present analysis is based on normal impact of projectile so the future works may also consider the obliquity of impact.
- In present work **FEVICOL SR 505** synthetic rubber adhesive is used as a bond material, to minimize the problem of debonding and to provide a safer structure different types of adhesive can be used.

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