Investigations of Laminated FRP Composites for Low Velocity Impacts

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Abstract— Fibre reinforced composites have become increasingly important over the past few years and are now the first choice for fabricating structures where low weight in combination with high strength and stiffness are required. Many of the new and innovative products are influenced by impact damage, whether by design or by accident. Impact properties such as damage resistance are crucial to product design. The present work is aimed at gaining an initial understanding of the impact behavior of fiberglass reinforced laminates with vinylester and isopolyester resins. The purpose of this research is to characterize the damage done to fiberglass laminates subjected to low velocity, high mass impact. The effect of adding a protective layer of rubber to the laminates is also investigated. Finite element models are created with ANSYS/Ls-Dyna nonlinear finite element software. These models are used to simulate the drop tower tests and extended to thicker laminates as well as different impact speeds and impact or mass. Several models are also created to predict the effects of the rubber protective layer. Several drop tower impact test were performed with a relatively high mass (5.5 kgs.) and a low velocity (2-4 m/s). These impacts produced severe damage in some of the laminates with only one impact. These models are able to predict approximate stresses and strains induced in the laminates during the impact which are compared to the damage from the drop tower tests. The models predicted that the rubber layer decreased the stress and strain in the laminate up to 50%. The drop tower tests confirmed that the rubber aided the impact resistance significantly.

Key words: Fibre Reinforced Composites, Vinylester, Isopolyester, ANSYS, Ls-Dyna

I. INTRODUCTION

FRP Composites have main structural applications in the field of military and commercial aircraft. The principal reason for using FRP in aircraft and helicopter structures is weight saving, which, depending on structure, maybe as high as 30% over the metallic counterpart. It also reduces the number of components and fasteners. Boron fibre reinforced epoxy skins are first used in F-14 fighter aircrafts horizontal stabilizer box. Carbon fibre reinforced epoxies are used in the construction of wings, rudder, fuselage and elevators of commercial aircrafts. FRP Composites are used in the rotor blades of helicopters. In addition to significant weight reduction over aluminium, FRP provides better control over the vibration characteristics of the rotor blades and manufacturing flexibilities.

Carbon fibre reinforced epoxy is used in antennas and supporting structures of telescope, reflectors, solar array and other parts in satellites and space stations. The main reason for selecting carbon fibre in epoxy is its low density and very low coefficient of thermal expansion. Fibrous composites are extensively used in automotive industry for body components such as door panels, door frame and for chassis components such leaf springs. FRPs are extremely corrosion- resistant and are in consequence, used for chemical plant, water transport and storage, and flue gas desulphurization plant. They have interesting electromagnetic properties. In medical field, artificial lungs are made of graphite- glass/ epoxy and Carbon fibre reinforced epoxy is used for X-ray tablets. Thermal properties can also be important due to the fact that such materials have a low thermal conductivity, making them useful for insulation. In addition to this FRP composites are used in sports goods and marine applications.

II. LITERATURE REVIEW

Early work on impact mechanics was inspired by the railroad industry, specifically the cars impacting the steel rails [1]. Thomas Young was one of the first to investigate impact on perfectly elastic material in the early 1800's. Young concluded that the energy absorbed by the beam was proportional to its volume. Saint-Venant [1] was also developing theories about impact around this time. Saint-Venant looked at a beam fixed at one end subjected to an impact blow at the other end. He simplified this problem to a vibrating beam with a mass attached to one end. Saint-Venant never fully solved this problem but laid the groundwork for the research that followed.

Experiments and research of impact continued into the twentieth century. The experiments consisted of falling steel balls hitting a target. J.E Sears [1] followed up on the work of Saint-Venant by conducting experiments with bars with spherical ends. D. Taylor [1] continued the study of impact of balls past the elastic limit. Timosheko and E. H. Lee [2] also followed Saint-Venant and others to come up with very detailed equations of motion related to impact in 1932.

J. D. Winkel and D. F. Adams [3] conducted some of the first experimentation with modern drop weight test fixtures in 1985. They used this test fixture to characterize the difference in impact damage between several types of composite laminates. They were able to gain time histories of the impact force by using a piezoelectric force transducer. Before the piezoelectric force transducers, strain gages were the most common tool for instrumenting these tests.

In 1994, G. Zhou [4] performed a study to determine the influence of impact force and incident kinetic energy during impact on composite plates. He performed this study using glass-fiber reinforced laminates with low velocity impact. A flat-ended impactor was used with energy ranging from 15-3000 J. After the samples were impacted they were C-scanned and cross-sectioned to determine their damage mechanisms. The damage mechanisms that absorbed the energy and controlled the load bearing capabilities were delamination, fiber shear-out, and fiber tear. Zhou determined that these damage mechanisms were geometry dependent and happens in a sequential order. He matched these sequences to the corresponding section of the force time curve from the drop tower tests. Zhou also concluded that the load and energy needed for damage was most affected by the laminate thickness and the load bearing capability was most affected by the in-plane dimension. G. Zhou along with G. A. O. Davies and D. Hitchings [5] also studied the post impact compressive strength of delaminated composites and concluded that their strength suffered greatly when delaminations were present. He also matched reasonably well the force-time characteristics of impact on 10 mm laminated plated with an FE model which accounted for geometric non-linearity.

Also 1994, Chun and Lam [6] solved the non-linear, second order differential equations governing the dynamic response of laminated composite plates. This was done in order to propose a numerical method for the calculation of the dynamic response of these plates under low velocity impact. Their results included stress, deflection, contact force, and energy transferred vs. time for several different stacking sequences. They compared their results to literature and stated that their proposed method could be used to analyze laminated plate with any stacking sequence.

In 1994 G. Zhou and G. A. O. Davis [7] used a drop weight test rig to investigate the impact response of thick glass/polyester laminates plates. Impact tests were conducted with a high mass (8-75 kg) and a low velocity impactor. This allowed more kinetic energy to be absorbed by the sample since there was relatively long contact duration. They determined the impact response and energy absorbing characteristics by studying the absorbed energy histories and the force-displacement relationships. Visual inspection, ultrasonic C-scan, and an optical microscope were used to observe the damage. The conclusions of this study was that the maximum static and impact forces, and the incident kinetic energy could be scaled by a thickness ratio if the samples have the same diameter and their behavior is dominated by shear. The major failure modes that they observed included matrix cracking, surface micro buckling, delamination, fiber shear-out, and fiber fracture.

A recent model was created for Ls-Dyna3D by Hou, Pentrinic, and Ruiz [16]. They improved the delamination criterion by including more of the stresses that contribute to the failure. They included interlaminar shear and through-thickness compression stresses as well as fiber failure and matrix cracking. They also stated that their model showed improvements in the damage prediction in composite laminates.

Several different ways of improving the impact properties of composite materials have been studied. Some of these include 3D weaving, 3D stitching, optimal stacking sequences, and combining fibers with different properties. It was found very early that unidirectional fibers will split at very low energies and are therefore not recommended for use on the outside edge of laminates. Laminates with -/+ 45º and 0º/ +/- 45º surface plies have shown much better impact resistance and residual strengths [17]. However, it has also been found that delamination is more likely between abrupt ply angle changes such as -/+ 45º [18].

The introduction of lower modulus fibers has also been shown to improve the energy absorption of the composites. Hancox and Wells [19] showed a 500% increase in energy absorption by introducing E-glass fibers with carbon fibers.

Cantwell, Curtis, and Morton [20] showed in 1983 that three-dimensional weaving and stitching significantly reduced the delamination in layered materials. This reduced delamination improved the impact response, the strength, and the residual properties of the laminate.

In 2000, Shankar and Zhu [21] published the results of a study about the effects of stitching on the low-velocity impact response of composite beams. They used numerical analysis to look at the response of the beams (which were already delaminated) reinforced with stitching. The stitches were modeled as shear tractions to provide shear resistance between the layers. The analysis consisted of a rigid ball impacting a simply supported beam. They also analyzed unstitched laminates for a comparison. They found that the stitching does not affect the load at which the delamination begins but it greatly reduces the spreading of the delaminations.

III. METHODOLOGY

A. *Statement of Problem*

The problem is to characterize the damage occurred to fiberglass laminates subjected to low velocity, high mass impact. This subject is a crucial design question that appears frequently in the design of new composite products. Impact loads affect almost all commercial composite products whether by design or by accident. This investigation attempted to provide initial insight into impact damage done to the fiberglass laminates by performing several drop weight impact analyses with finite element models and predicted the behavior of the laminates under different impact situations. Further research is needed to evaluate the effects of impact damage on specific applications.

B. *Non- Linear Analysis*

The non- linearity arising from the nature of material is called ‘Material Non- linearity’. All non- linearities are solved by applying the loads slowly (dividing it into a number of small load increments). The model is assumed to behave linearly for each load increment, and the change in model shape is calculated at each increment. Stresses are updated from increment to increment, until the full applied load is reached.

In a non- linear analysis, initial conditions at the start of each increment is the state of the model at the end of the previous one. This dependency provides a convenient method for following complex loading histories, such as a manufacturing process. At each increment the solver iterates for equilibrium using a numerical technique such as Newton Raphson method. Due to the iterative nature of the calculations, non- linear FEA is computationally expensive, but reflects the real time conditions more accurately than linear analyses.

C. Elements Used

Due to advantages and disadvantages of one element over the other, as well as the parameters to be determined in view, two elements are used in the total analysis. They are Shell 163 element and Solid 164 element.

1) Shell163 Element

SHELL163 is a 4-node element with both bending and membrane capabilities [22]. Both in-plane and normal loads are permitted. The element has 12 degrees of freedom at each node: translations, accelerations, and velocities in the nodal x, y, and z directions and rotations about the nodal x, y, and z-axes. This element is used in explicit dynamic analyses only.

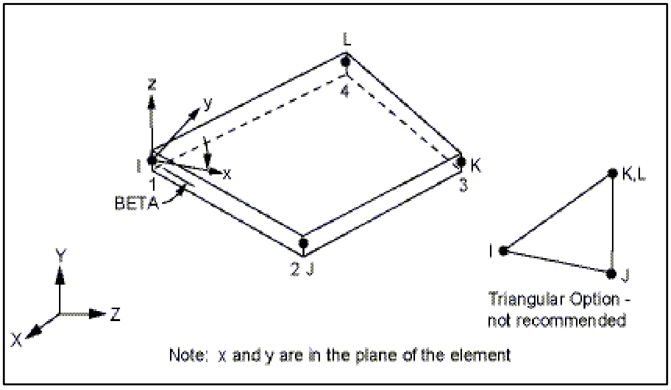


Fig. 1: Shell 163 Element

2) Solid164 Element

SOLID164 is used for the 3-D modeling of solid structures. The element is defined by eight nodes and nine degrees of freedom at each node: translations, velocities, and accelerations in the nodal x, y, and z directions. This element is used in explicit dynamic analyses only. This element cannot be used for models in which interlaminar stresses are to be predicted. This solid element uses an effective modulus through the thickness of the layer by averaging the elastic modulus of all the layers. This becomes a problem when the layers have drastically different moduli from layer to layer as in fiberglass laminates. This element will not take into effect the position in the laminate of the very high or very low modulus layers, which plays a key role in the bending of the laminate. It will also give inaccurate interlaminar stresses since the adjoining modulii are the key parameter for that calculation. Therefore, macroscopic laminate properties are used with this element. However, far more information can be retrieved through post processing with the solid elements rather than the shell elements. With these solid elements a difference can be seen between the deflection and stresses on the top of the target and the bottom of the target. The solid element model is also more flexible when changing the parameters such as laminate thickness and adding the protective rubber layer.

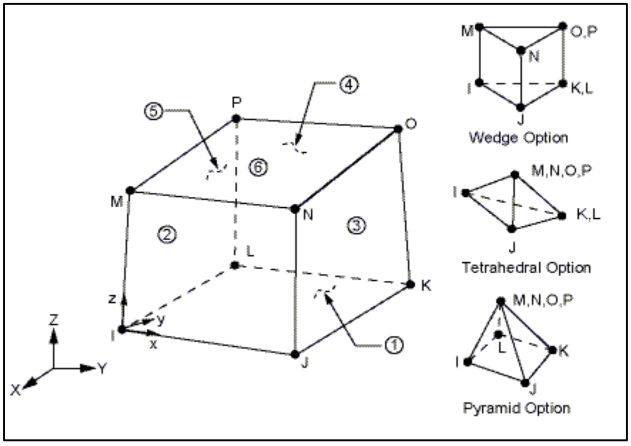


Fig. 2: Solid 164 Element

D. Material Properties

In the present analyses, the material properties for the isotropic bodies (impactor) are specified normally, whereas for the composite bodies (target plate), the material properties, instead of giving them individually for each layer, the effective properties of all the layers combined together are given.

E. Solver used: Newton Raphson Method

As discussed earlier, in a non-linear analysis, the loads are applied in an incremental manner instead of applying in a single go. Also the elements of the stiffness matrix are a function of the displacement matrix.

Hence such equations of equilibrium cannot be directly solved and we need the aid iteration techniques to achieve solution to such problems. Newton Raphson method is the widely used technique to arrive at the solution for non-linear problems.

Concept of Time: we have discussed that the loads in a non-linear analysis loads are applied in an incremental manner. Hence while simulating such behavior we specify the load as a function of time. The time is just used to define the pattern in which the load should be increased for the model. The time specified here is completely a pseudo time and cannot be mistaken with the real time that is used to apply time varying loads in a transient analysis.

Concept of Load: while applying loads to FE models with respect to time (Either in transient analysis or for a non-linear analysis with pseudo time), at the beginning of each step the load can be increased and kept constant till the end of that time step. Such a loading pattern is called stepped loading.

Hourglass energy: In dynamic finite element analysis, the hourglass energy is a large concern. Hourglass modes are unnatural modes that do not produce strain energy even though the element is deforming. These modes are very common in impact analysis but should be kept to minimum. As a general rule the hourglass energy should be kept below 10% of the total energy of the model. Flanagan-Belytscko stiffness form of hourglass control is used to lower the hourglass energy throughout all analyses.

IV. PARAMETRIC STUDY

In order to predict how the FRP composite material will behave under different impact situations, a study is performed using finite element models. The models are adjusted to simulate different impact energies by varying the impactor mass and speed. Four models (without rubber) are constructed to look at the effects of the mass and four are created for the impactor speed. The models with the varied mass included 2.25, 5.5, 9 and 22.5 kg impactors and the velocities included 1, 2, 2.5, and 3.81 m/s impact speeds. The speed of 2.5 m/s is used to create a situation where a different combination of mass and velocity resulted in the same kinetic energy (1/2 mv^2) in the two simulations. The mass of 5.5 kgs and the velocities of 2 and 3.81 m/s correspond to the drop test conditions. This study is performed in the same regions as the test in order to correlate the two together and look for relationships between force, energy, and damage.

Interlaminar stresses are the most useful parameters in laminated composites subjected to impact loading. However, this model does not include layer data therefore interlaminar stresses are not computed by ANSYS/Ls-Dyna. Von Misses stresses also are not as useful in this situation due to the anisotropic nature of the composite. For this study it is decided to compare Z stresses since they were the highest in-plane stresses in the laminates due to the anisotropic nature of the composite.

A. Adjusted Mass

The mass is adjusted in the solid 164 models in order to look at how the stress and strain in the target change as the mass is increased. Since energy is the most common basis for comparison, a graph of stress and strain vs. energy, figure 4.1, is observed for possible connections to damage.

From the graph it is observed that the stress and strain both increase quickly at first as the mass is increased then level off. Damage will most likely occur in all four of these situations, especially the 2nd, 3rd, and 4th.

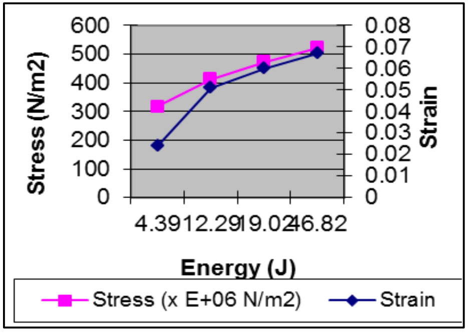


Fig. 4.1: Max in-plane stress and strain as impactor mass is increased.

B. Adjusted Speed

The impact speed is also adjusted in the solid 164 model in order to understand the role that the speed plays in the stress and strain in the target. Figure 4.2 shows the maximum stresses and strains in the target laminate as the impact speed is increased from 1 m/s to 3.81 m/s.

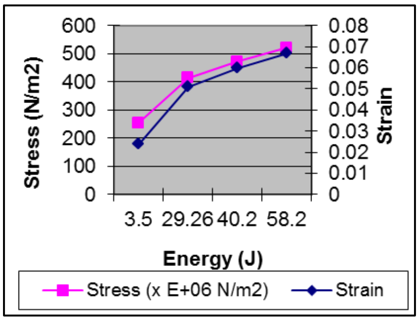


Fig. 4.2: Max in-plane stress and strain as impact speed is increased.

The maximum stress and strains level off slightly after 2.5 m/s but not as much as when the mass is increased. Overall the mass and the speed appear to have equal influence on the stress and strain levels seen in the composite.

C. Thick Laminates

ANSYS/Ls-Dyna models are also used to predict the effect of increasing the laminate thickness from 6 mm, 12.5 mm and 20 mm. The same impact velocity and mass of 3.81 m/s and 5.5 kgs is used in this comparison. Table 4.1 is a summary of these results.

Thickness (m)	**Maximum Z Stress (N/m2)**	**Maximum X Strain**
0.006	651.7 E+03	0.0185
0.0125	253.4 E+03	0.009
0.020	152.6 E+03	0.006

Table 4.1: Maximum in-plane stress and strain in three laminates of different thickness.

Figure 4.3 shows the maximum stresses and strains from the models of the laminates. Increasing the laminate thickness lowered both the stress and strain considerably, especially in the first step from 6 mm to 20 mm.

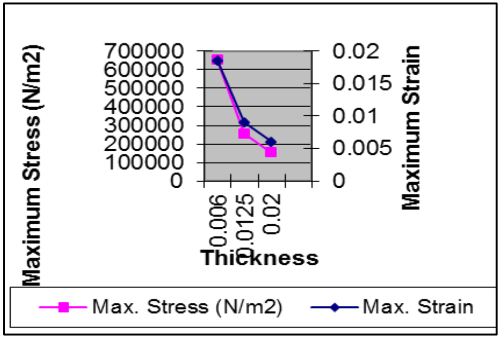
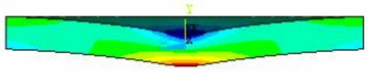
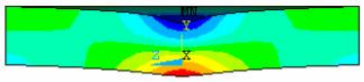


Fig. 4.3: Maximum in-plane stress and strain in laminates of different thickness.

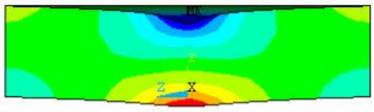
The maximum stress penetrated relatively the same distance into the laminate when the thickness was increased. This maximum stress however was significantly lowered as the thickness was increased. Figure, 4.4 shows the difference in the stress patterns in a 6 mm. laminate compared to a 12.5 mm and a 20 mm laminate. The 20 mm laminate may hold up to an impact of this caliber (5.5 kgs and 3.81 m/s) without noticeable damage since the maximum stress is below 210 x10^{6} N/ m^{2}. A test would be needed to verify this assumption.



0.006 m
Max. Stress = 609 E+06 N/ m2



0.0125 m
Max. Stress = 252 E+06 N/m2



0.020 m
Max. Stress = 154 E+06 N/ m2

Fig. 4.4: Maximum stress with variation in laminate thickness.

V. CONCLUSIONS

The purpose of this research is to examinee the impact response of fiberglass reinforced laminates. Several drop weight tower impact analyses are performed on 12.5cm x 12.5 cm FRP plates with resins including vinylester and isopolyester. These test simulated high mass (5.5 kgs) and low velocity (2-4 m/s) impact.

ANSYS/Ls-Dyna non-linear finite element analysis program is used to predict the stresses in the laminates during the impact. These stresses are then compared to the damage from the drop tests. The critical stress range for impact damage is in the range of (175-245) $x10^6$ N/m^2, which is very close to the static ultimate strength of the Duraspan laminates. The observations and conclusions of this research include the following:

A. Finite Element Analysis

1) Approximate stresses and strains are achievable with ANSYS/Ls-Dyna but more specific models are needed for more exact predictions.
2) Shell elements in the target mesh predicted the impact force slightly better than solid elements. However, much more information could be retrieved through post processing with the solid elements.
3) The predicted impact force is approximately 10-30% higher than the force in the experimental data. This is due to the model not taking into account the energy lost due to matrix cracking and delamination damage.
4) By comparing the FEA models to the damaged samples, the damage appears to correspond to an in-plane stress range of 175-245 $x10^6$ N/m^2.
5) The model of the rubber protective layer worked well at low velocities but had problems with penetration at higher velocities.
6) Increasing the mass and speed of the impactor has approximately the same effect on the maximum stress and strain in the target surface.
7) Laminate thickness had a large influence on the predicted stress and strain in the composite. Even small thickness increases significantly lowered the predicted stress and strain.

VI. FUTURE WORK

From the observation stated in this thesis, the critical stress range on the bottom surface of the laminates seems to be in the 175-245 $x10^6$ N/m^2 range. Further investigation can verify and possibly narrow this range for certain laminates and finds the stress level at the onset of damage. Once this range is verified, the ANSYS/Ls-Dyna models will be an even more valuable tool for designing new composite products.

ANSYS/Ls-Dyna also has an element failure option. Ultimate strengths of the materials can be set so that once that stress is encountered, the element is eliminated and the load is transferred to the other elements. This requires more investigation into the failure loads of the laminates and further work with the composite layer option in ANSYS/Ls-Dyna.

The rubber protective layer appears to aid the impact properties of the composite significantly. More testing and finite element modeling can further justify the use of a rubber protective layer in specific applications and aid in selecting the correct material and thickness. ANSYS/Ls-Dyna, as well as other contact codes, still has some problems with contact between materials with a large difference in material properties. The modeling capabilities presented in this thesis are severely limited by penetration problems with the rubber material. This research also provides a Ground work for much future technological advancement in the field of Material Science.

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