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MULTIPLE LAYER COMPOSITE PLATES IN BALLISTIC APPLICATIONS – A PARAMETRIC STUDY

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Abstract

A series of ballistic tests of single and multilayered composites has been conducted. Multiple monolithic composite plates were impacted by an aluminum projectile with an incident velocity of 500 m/s. As a means of comparing the impact energy absorbing capacity of composite laminates, the amount of absorbed impact energy was normalized by the total surface weight of glass fiber reinforcement. The tests gave some seemingly contradictive results. On one hand they showed that it was more efficient to utilize one thick composite plate than several thinner composite plates containing the same total amount of glass fiber reinforcement. They also showed that a thin composite plate will absorb a higher amount of specific impact energy than a thick composite plate. During the tests incident velocity and residual velocity were measured, as well as the test specimens being filmed using a digital high speed video camera.

1 Introduction

Light vehicles such as the High Mobility Multipurpose Wheeled Vehicle, HMMWV or Hummve, are usually protected against projectiles and blast shrapnel from road side bombs by add on ballistic protection panels. Most such ballistic protection panels are made from armor steel plates. This obviously adds a quite substantial weight to a relatively small vehicle. By combining structural panels and ballistic protection panels into one, it might be possible to save a substantial amount of weight. The reduced weight can then be used to increase a vehicle's agility, its range, or its payload. A similar application is deployable containers used either for storage of sensitive goods or for forward command centers. Such containers are also protected by ballistic protection panels which are added on to an existing structure and which do not add to the structural strength. In the same way as for vehicles it should be possible to combine structural panels with ballistic protection panels, thus making them easier to move around or increasing their payload.

Ballistic impact response of monolithic fiber reinforced composite laminates have been investigated by e.g. Wu and Chang [1] who found that the contact force was dependent on the mass of the projectile, but the absorbed energy was not. That was found only to be dependent on impact energy. Mines et al [2] investigated high velocity impact response of three different reinforcements; glass, aramid and polyethylene fiber. They found that delamination made a major contribution to energy absorption. Gellert et al [3], in their study of the thickness dependence on impact performance for glass fiber reinforced laminates, found the indentation phase to be significant. A study by Naik and Shiraro [4] shows that tensile failure of primary yarns and deformation of secondary yarns is the main energy absorbing mechanisms. Primary yarns were defined to be the ones that were in contact with the impactor, whereas secondary yarns were defined to be the ones displaced by the deformation of the primary yarns.

On sandwich structures, comparisons between quasi-static and ballistic impacts have been conducted by e.g. Wen et al. [5] and Reddy et al. [6], who presented theoretical models for predicting skin failure, empirical models for predicting penetration and energy absorption as well as experimental data. Mines et al. [7] conducted ballistic impact tests of woven, z-stitched and through the thickness z-stitched glass fiber reinforced polyester laminates. They found that the three different constructions failed in a similar way. Roach et al. [8,9] investigated the impact energy absorption of monolithic laminates and sandwich plates and found that the monolithic laminates absorbed more impact energy. Perforation of multilayered aluminum beams, by Marom and Bodner [10] and Radin and Goldsmith [11], showed that several thin aluminum beams separated by air absorbed less impact energy than a solid aluminum beam of the same weight. Almohandes et al [12] investigation on steel plates, and steel FRP hybrid also showed that a single layer absorbs more energy than several layers of the same total weight spaced by air.

In the current study, the effect of the core material in a sandwich panel on the ballistic impact energy absorption has been investigated as well as the relatively low efficiency of using multiple laminates separated by air. The tests conducted include single and multiple monolithic laminates as well as sandwich plates and acrylic plates. The latter was used in order to study the interaction between the separate plates. They were transparent and thus made it possible to film the impact event using a high speed camera. For comparison of the efficiency of the laminates, the specific energy absorption was used. It was defined as the amount of energy absorbed divided by the total surface density of the fiber reinforcement within the laminate. It was believed that this would provide a good measure of the efficiency of a laminate considering that the current study focused on laminates used in mobile weight sensitive structures.

2 Test equipment

The test set up consisted of a compressed air gun with an exchangeable barrel, figure 1. In the current tests a 20 mm caliber 2000 mm long barrel was used. The gun was fed compressed air from a scuba dive compressor capable of maximum 250 Bar. The max pressure used in the current tests was 200 Bar, resulting in an incident velocity of slightly above 500 m/s.

The gun was equipped with a recoil damper / diffuser at the muzzle to reduce the recoil somewhat, but mainly to reduce the amount of air following the projectile, thus reducing the influence of the blast from the gun on the test specimen. In addition, a blast shield was placed in front of the test specimen to further reduce the influence of the gun blast.

Placed between the gun muzzle and the blast shield was a Gamma Master Chrony speed trap used to measure the incident velocity. The residual velocity was measured using a kinematic pendulum to catch the bullet after it had passed through the test specimen [13,14]. The displacement of the pendulum was measured using a linear variable differential transformer (LVDT). From the measured displacement of the pendulum the residual velocity and energy was calculated.

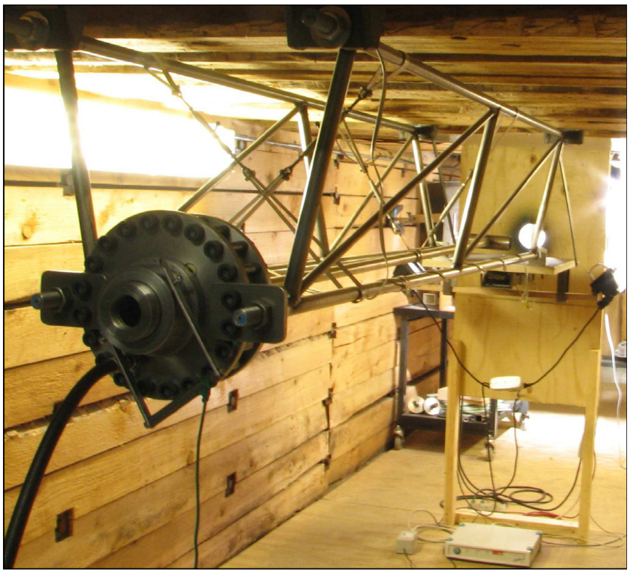

Figure 1. The compressed air gun facility

In the impact tests in this study a 20 mm diameter and 35 mm long EN-AW 6082 aluminum projectile with a hemispherical head was used. Aluminum was chosen in order to achieve a relatively low weight projectile. The aluminum quality was chosen to keep the amount of plastic deformation of the projectile to a minimum. In order to reduce the mass and increase the directional stability of the projectile, a 14 mm diameter and 18 mm deep hole was drilled in the rear of the projectile. The weight of the projectile was approximately 18.8 g. Figure 2 shows the dimensions of the projectile.

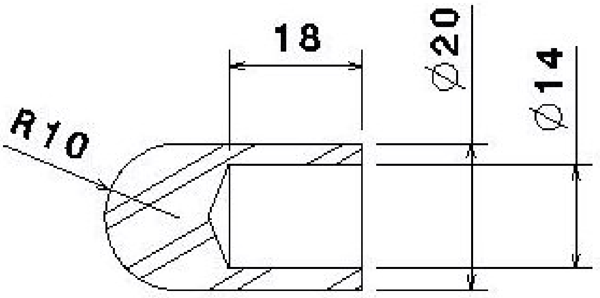

Figure 2. Sketch of the EN-AW 6082 aluminum bullet used in tests

An Olympus i-speed digital high speed video camera was used to monitor the tests. A frame rate of 8000 -- 10000 frames per second was used in order to capture the projectile, the delamination growth and waves in the surface of the test specimen.

3 Ballistic impact tests

All the composite laminates tested were manufactured from layers of non crimp fabric (NCF) E-glass fiber and Pro Set 117/229 epoxy. They were all manufactured by vacuum infusion and post cured at 50 °C for 24 hours. Prior to infusion, the epoxy was subjected to approximately 99.9 % vacuum for 30 minutes in order to reduce the amount of air dissolved in the epoxy. Two different NCF's were used; one with a stacking sequence of [0°, 90°] weighing 650 g/m², and one with a stacking sequence of [0°, +45°, 90°, -45°] weighing 850 g/m².

The multiple laminates tested all had the same total amount of fiber as the reference single laminate.

The sandwich plates tested consisted of face sheets of the same materials as the monolithic laminates with either Divinycell H30 or H200 PVC foam core material.

In addition to glass fiber reinforced epoxy laminates, NCF's stacked without any epoxy and NCF's bonded with 3M #77 glue were tested. Acrylic plates were also tested, not to investigate their suitability as ballistic protection but to observe the interaction between plates spaced with gaps of air.

3.1 Reference laminates

A laminate consisting of 10 layers of 650 g/m² NCF and epoxy was chosen as a reference laminate. It had the following stacking sequence; $[0°, 90°]_{10}$ yielding a laminate thickness of approximately 4.8 mm. The results presented are therefore all normalized by the results for the reference laminate. The influence of the stacking sequence on the energy absorbing capability was investigated by testing laminates with the following stacking sequence, $[0°, 90°, +45°, -45°]_5$. These laminates had the same thickness as the reference laminates.

Since multiple laminates separated by air were being tested it was also decided to test single laminates of the $[0°, 90°]_5$ stacking sequence too.

3.2 Multiple laminates

As a first step to study the influence of the core material on ballistic impact energy absorption a series of two laminates separated by an air gap was tested, thus entirely removing the influence of the core material. Two $[0°,90°]_5$ laminates with a nominal thickness of 2.4 mm were used. The air gap separating them was 10 mm, 20 mm, 40 mm, 60 mm and 80 mm.

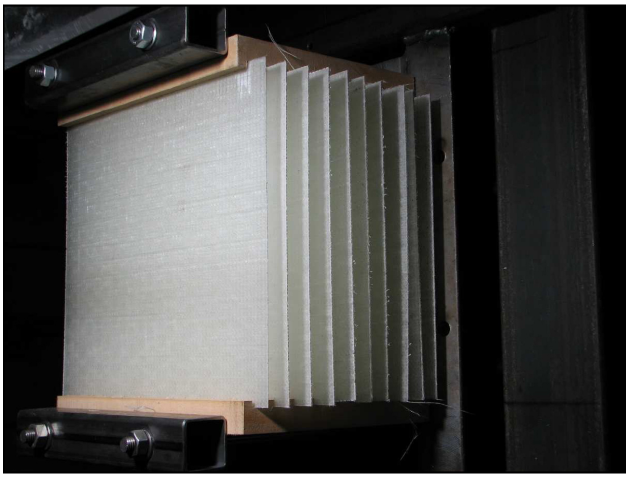

Figure 3: Test set up of 10 plates of 1 layer laminates

It was found that the amount of specific energy absorbed was significantly lower for the twin laminates than for the single reference laminate. Therefore it was decided to run tests with multiple laminates separated by a gap of air. The total amount of [0°,90°] NCF's used were kept to 10 for all the tests. The multiple laminate series consisted of 5 $[0°,90°]_2$ laminates separated by 20 mm air gap and 10 $[0°,90°]_1$ laminates separated by a 10 mm air gap. The latter is shown in figure 3.

3.3 Laminates without resin

Since the influence of the core material in a composite sandwich was investigated by not using a core material, it was equally easy to go one step further and investigate the influence of the resin by not using resin in the laminates. Obviously, a laminate without resin is no laminate as such, but it was believed that it could possibly add valuable results to the tests.

For the layers of dry NCFs to stick together they were bonded to a medium density fiber (MDF) frame using either contact glue or 3M \#77 glue. On half of the test specimens the entire surface of the NCFs were covered with glue, and the other half were only covered with glue along the edges. The stacking sequence used was [0°, +45°, 90°, -45°]$_3$.

3.4 Sandwich plates

The sandwich plates tested consisted of two face sheets of [0°,90°]$_5$ separated by a PVC foam core. Two different core densities were used, Divinycell H30 with a nominal density of 30 kg/m^3 and Divinycell H200 with a nominal density of 200 kg/m^3. The former was 20 mm thick and the latter was 25 mm thick.

3.5 Acrylic plates

The tests in the previous sections showed that multiple layers of laminates with air gaps between them did not perform as well as a single laminate with the same total mass of fibers. To investigate what could be the cause of this it was decided to test a brittle and transparent material which would crack before surface waves developed. Thus keeping the out of plane movement to a minimum, and making it possible to study the impact event with a high speed camera. Three series of tests were conducted, the first with a single sheet of acrylic glass as reference, the second with two sheets of acrylic glass and the third series with four sheets. The sheets used in the second and third series were spaced with an air gap of approximately 20 mm between them.

Figure 4 shows the instance when the first acrylic plate is hit by the projectile. Several cracks have developed, some debris is thrown forward in front of the projectile, but there is little visible local bending deformation in the plate outside the point of impact.

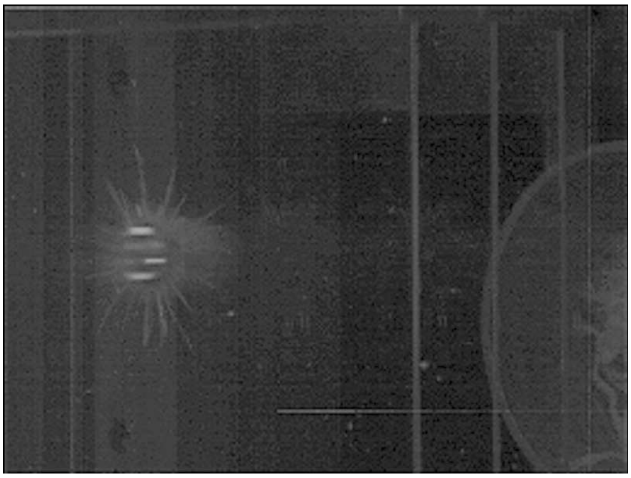

Figure 4. First acrylic plate of four hit by 20 mm projectile

In figure 5 all four plates have been penetrated by the projectile. It can also be seen that the holes in the acrylic plates increase in a conical shape, where the first plate has a hole which is little larger than the projectile. The hole in the fourth plate cannot be seen because the plate has fallen apart.

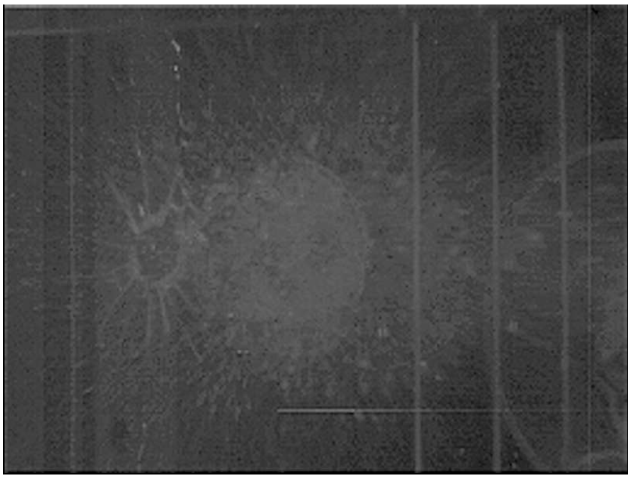

Figure 5. Four acrylic plates penetrated by 20 mm projectile

4 Results and discussion

As a means to compare the energy absorbing capacity of a composite laminate, specific energy absorption was used. In this study, specific energy absorption is defined as the measured energy absorbed divided by the surface weight of the reinforcement of all the composite plates. The weight of the resin, and for the sandwich plates, the weight of the core material is not considered.

$$\mathrm{E}_{\mathrm{t}} = \frac{E_i - E_r}{Y_t}, \ where \ Y_t = \sum_{i=1}^{n} (Y_i) \qquad (1)$$

In equation (1) E_i is incident energy calculated from measured incident velocity, E_r is residual energy as measured with the kinetic pendulum, and Y_i is the nominal surface density of each layer of NCF. In the current study Y_i=650 g/m², or Y_i=850 g/m² depending on the NCF used.

4.1 Single laminates

There was a relatively large scatter in the measured specific energy absorption observed in the results, see table 1. However, the results still indicate that a thin laminate is capable of absorbing a higher amount of specific impact energy than a thick laminate. One reason for this may be that a thin laminate allows for a larger out of plane deformation before failure than a thick laminate. Another explanation can be found in the fact that, given a certain measurement accuracy, the measured specific energy absorption will tend to go towards infinity when the surface density goes towards zero. Therefore, using specific energy absorption as a means to measure the impact energy absorbing efficiency of very thin laminates may not be valid. It is, however, believed that for laminates of reasonable thickness, from a structural point of view, it is a good measure for comparing the energy absorbing efficiency of different laminate designs.

Table 1. Impact energy absorption from single composite plates. N refers to the number of [0°, 90°] layers in the laminate, v_i is incident velocity in m/s, E_s is specific impact energy absorption in [J/(kg/²)], s is standard deviation, and E_{Rel} is specific energy absorption relative to the reference laminate.

Series	N	v_i [m/s]	E_s	s	E_{Rel}
A	10	506	116	8	1.00
B	5	501	143	15	1.23

4.2 Multiple laminates

Based on the very high specific energy absorption measured for the thinnest single laminates in the previous section, it could be reasonable to expect that a series of thin laminates placed after each other would be capable of absorbing more energy than one single laminate of the same total thickness. That was, however, found not to be the case. Table 2 shows the results from the tests of multiple laminates separated by a gap of air, and for the sandwich plates.

Table 2: Impact energy absorption from multiple composite plates. † indicates that the specimens were sandwich plates, N_l refers to the number of laminates, N refers to the number of [0°, 90°] layers in each of the laminates, δ is the distance in mm separating the plates, v_i is incident velocity in m/s, E_s is specific impact energy absorption in [J/(kg/²)], s is standard deviation, and E_{rel} is specific energy absorption relative to the reference laminate.

Specimen	N_l	N	δ	v_i	E_s	s	E_{rel}
B	2	5	20	512	101	8.3	0.88
C	5	2	20	509	125	5.8	1.08
D	10	1	10	508	121	n.a.	1.04
E†	2	5	20	525	133	2.9	1.15
F†	2	5	25	525	141	0.5	1.22

It became quite clear that separating laminates by a gap of air was not beneficial, which was expected from the results in the previous section. Separating the laminates by a core material, however, did look promising. The calculation of the specific energy absorption did not take the added mass of the core material into account. The light core material had a density of 30 kg/m³ and a thickness 20 mm, which added approximately 10 % to the surface weight of the plate. Taking the measurement accuracy into account the added weight was almost the same as the added specific energy absorption. By comparison the heavy core material had a density of 200 kg/m³ and a thickness 25 mm, and thus added approximately 77 % to the surface weight of the plate. Therefore it could not be assumed that the contribution of the core material to the specific energy absorption was directly related to the core material density.

4.3 Laminates without resin

Observations from high speed photography of the ballistic impact tests and form visual inspection the laminates post impact showed a significant variation in the size of the delaminated area around the point of impact. The difference in delaminated areas around the point of impact did, however, not seem to affect the measured energy absorption. Therefore it was decided to test some laminates without any resin in order to investigate its effect on the energy absorption. The results are shown in table 3.

Table 3: Impact energy absorption from laminates without resin. ‡ indicates a specimen which was soaked in soap and water, N refers to the number of [0°,+45°,90°,-45°] layers in the laminate, v_i is incident velocity in m/s, and E_s is specific impact energy absorption in $[\mathrm{J}/(\mathrm{kg}/^{2})]$.

Specimen	N	v_i	E_s
Reference	3	513	252
Dry	3	515	235
Dry‡	3	512	209

The reduction in specific energy absorption due to the removed resin was within the expected measurement accuracy of the test setup. In a common laminate each fiber is, in the ideal case, entirely surrounded by resin which reduces the amount of resistance due to friction when deforming the laminate. When the resin is not present, it is reasonable to assume that there will be a certain amount of resistance to displacement due to friction. Therefore, one specimen was soaked in soap and water in order to try to reduce the amount of friction. The observed reduction in specific energy absorption may be due to the reduced amount of friction, but since only one test was conducted it would be difficult to say with certainty.

4.4 Acrylic plates

The reduction in specific energy absorption became very pronounced in the results for the acrylic plates. As can be seen in table 4, four plates separated by an air gap only absorb a third of the energy per plate that one single plate does. High speed photography of the impact showed that thrown out material from the first plate damaged the next plate. The size of the hole in the plates increased in a conical shape from the first to the last plate. In the tests with four plates; the first plate had a hole slightly larger than the projectile, the second and third plate had holes of increasing size, and the last plate broke into several pieces because the damage was too big.

Table 4: Impact energy absorption from transparent sheets of acrylic. δ is the air gap between the plates, v_i is incident velocity in m/s, and E_t is absorbed impact energy, in J, divided by number of plates.

Specimen	δ	N	v_i	E_t
Acrylic 1	n.a.	1	425	578
Acrylic 2	20	2	428	328
Acrylic 4	20	4	429	191

The high speed photography showed that the plates did not deform visibly during the impact. They cracked and failed close to the point of impact before surface waves could develop. From the above results it was found reasonable to assume that the reduction in efficiency when using multiple plates spaced by a gap of air was not due to inhibited movement of the plates. It was however found reasonable to assume that the reduction in efficiency was due to thrown out material from one plate to the next. The thrown out material was assumed to have a sufficiently high kinetic energy to damage the next plate.

5 Conclusion

Ballistic impact tests of composite laminates have been conducted. The laminates have been tested one by one, and with two or more laminates placed after each other separated by air or a core material. From these tests it was found that a single thin plate had a higher specific energy absorption than a single thick plate. From those results it was expected that using multiple plates could be beneficial for energy absorption. That was, however, not found to be the case. Multiple plates separated by a gap of air had lower specific energy absorption than a single plate of the same total thickness as the multiple plates. Using a core material instead of air between two plates, i.e. a sandwich, was found to be slightly better than using a single plate.

Thrown out material was found to be one contributing reason to the reduction in specific energy absorption when using multiple laminates separated by a gap of air. Material thrown out from one plate damaged the next plate.

It was also found that the resin in the laminates tested did not contribute to the amount of energy absorbed during ballistic impact.

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