The Use of Glass Reinforced Plastic as a Flask Energy Absorbing Material

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INTRODUCTION

Irradiated fuel transport flasks are designed to survive impact and fire accidents without significant leakage of contents. The impact standards laid down by the IAEA include a drop test from a height of 9 metres, in the most damaging attitude, onto a flat unyielding target. This requirement leads to the incorporation of energy absorption features for impact protection. Such features may be integral with the flask body and/or lid, as seen on the CEGB's Magnox MkM2 and AGR MkA2 flasks. Alternatively, it may be operationally more convenient to have removeable energy absorbers, as on most LWR flasks and the CEGB's AGR MkA1 flask.

This paper is concerned with the design of removeable energy absorbers and the materials which may be used in their construction. In order to address the design issues, a notional cylindrical flask of 10 tonne mass is considered. To allow a design margin, and to cater for all future requirements and possible changes in regulations etc., the drop height considered is increased to 36 metres.

DESIGN

Consider a cylindrical flask with cylindrical energy absorbers attached to each end, as shown in figure 1. More complex shapes of absorber are possible of course, but this simple example serves to illustrate the design principles.

In general, after primary impact at an arbitrary angle, part of the impact energy has gone into deformation of the energy absorber and part is transferred into residual translational and rotational kinetic energy which will be absorbed by secondary and subsequent impacts. It is possible to calculate this energy partition by rigid body mechanics (Dallard 1985), but the method will not be described here.

From the energy to be absorbed, E_a, it is also possible to calculate the crush distance, d, the crush volume, V, the crush footprint area, A, and the peak load, F_p, given the absorber's 'crush stress', σ_c, from the following equations.

$$E_a = \sigma_c V \qquad F_p = \sigma_c A$$

The equations are based on the simple assumption that the absorber crushes at a stress which is independent of contact area and velocity. Volume and area are assumed to be adequately approximated by the truncated volume and area. For inhomogeneous materials, the crush stress is simply defined as the crush load divided by the contact area.

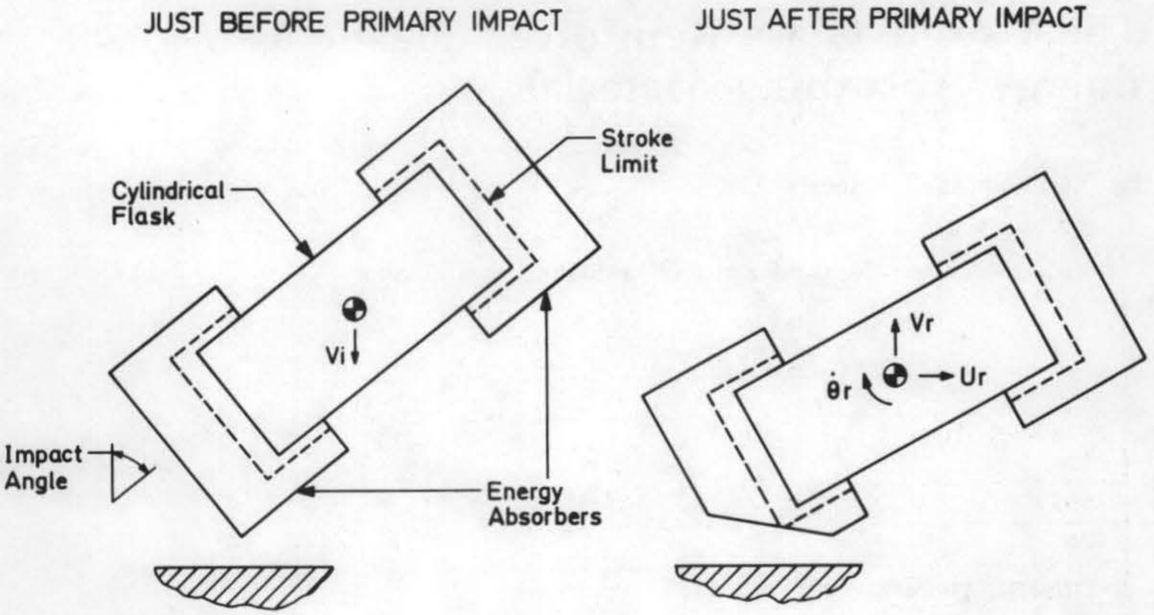

Figure 1. Impact of Cylindrical Flask

The maximum crush distance is fixed by the maximum size of energy absorber (which is dictated by handling requirements, train and truck design and the allowable height of the centre of gravity) and the stroke efficiency (the fraction of useable crush distance before the absorber 'bottoms' with unacceptable rise in load). Given this constraint, it is the crush stress which must be adjusted in order to minimise the loads on the flask.

Note that the flask itself must be designed to withstand at least these minimum loads, since it is not possible to reduce them within the limitations on absorber size. This conclusion is independent of any considerations of absorber materials. However, if greater loads can be withstood, then a material with a greater crush stress than the minimum can be used.

The calculations have been performed for a flask of 1m diameter, 2m length and 10 tonne mass with an absorber on each end of 1.2m diameter, 0.8m length, 1 tonne mass and 70% stroke efficiency, overlapping the flask by 0.3m. Results are given in Table 1.

Impact Angle (deg)	Fraction of Energy in Primary Impact	Allowable Crush Distance (m)	Required Minimum Crush Stress (MPa)	Peak Load On Flask (MN)
0	1.00	0.350	11	12
15	0.99	0.356	18	21
30	0.99	0.338	38	29
45	0.88	0.297	60	30
60	0.69	0.236	78	30
75	0.50	0.158	93	33
90	0.50	0.070	99	45

Table 1. Variation of Key Parameters with Impact Angle

CANDIDATE MATERIALS

Materials already in use in flask energy absorbers include balsa, hardwood, mild steel or aluminium fabrications and aluminium honeycomb. The CEGB's flasks with integral absorbers use plastic flow of mild steel in compression. The approximate crush stresses and specific energy absorption (i.e. energy absorption per unit weight) of these materials and some others are given in Table 2.

Material	Mean Dynamic Crush Stress (MPa)		Specific Energy Absorption (kJ/kg)
	Axial	Transverse	Axial
Solid Mild Steel	1600	1600	50
Mild Steel Tubes or Fabricated Plates	15-100	5-40	10-50
Solid Lead	130	130	3
GRP	50-150	?	30-70
American Oak (Constrained)	55	18	55
Aluminium Honeycomb	1-45	< 5	15-55
Balsa (Unconstrained)	8-13	4-9	30-45
Balsa(Constrained)	20-30	4-9	70-100
High Density Phenolic Foam	5	5	6

Table 2. Approximate Crush Properties (CEGB Data)

Note that the constrained wood results are for material crushed in a rigid cylinder and are unlikely to apply in practical absorber designs. The mild steel tube and plate upper bound properties are appropriate to the limit of what is feasible to manufacture due to wall thickness and cell size.

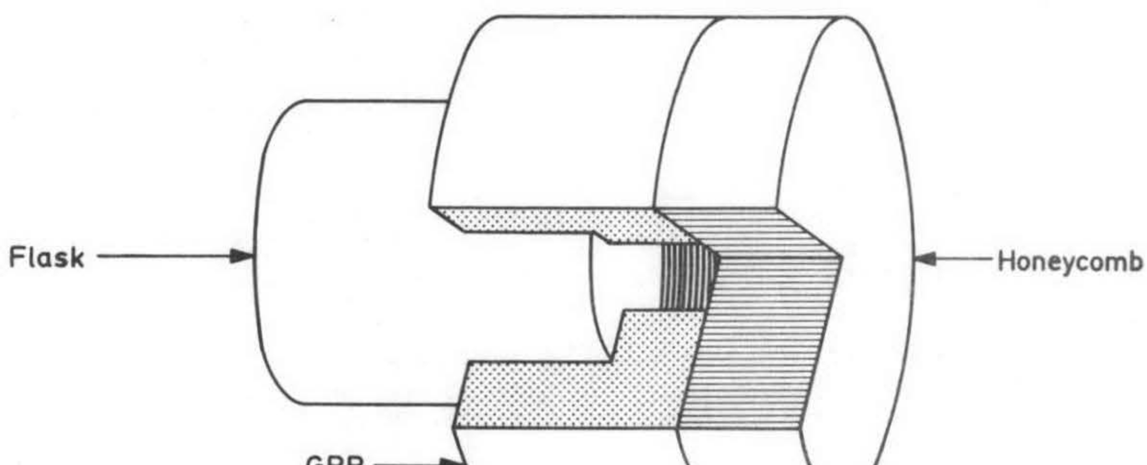

Figure 2. Conceptual Design of Energy Absorber

It would be difficult to devise a structure made of any one of these materials which exhibited the degree of anisotropy of crush stress required from the example in the previous section. A possible solution to this problem would be to use a composite of two materials. One, of low crush stress, would deal with impact angles from axial to about 20 degrees, whilst the other, of higher crush stress, would deal with angles from 20 degrees to transverse. The former material requires a minimum crush stress of about 25 MPa, for which aluminium honeycomb would be suitable. For the latter, a minimum crush stress of about 100 MPa is required, for which either a mild steel fabrication or GRP would be suitable (solid lead can be rejected because of its very low specific energy absorption).

A conceptual design in honeycomb and GRP is shown in Figure 2. (Note that table 1 should strictly now be recalculated for this new geometry, but the results are not given here for lack of space.)

SELECTION CRITERIA

Selection from the candidate materials can be made on the basis of the following criteria.

1. Quality assurance and manufacturing repeatability.
2. Scalability of manufacturing and of impact properties.
3. Repeatability of impact properties.
4. Anisotropy of crush stress.
5. Longevity.
6. Cost.
7. Weight.
8. Property stability over a temperature range of -40 to +40 ° C.
9. Performance in fire

There is evidence that GRP offers advantages over steel fabrications in many of these areas. Quality assurance and manufacturing repeatability of GRP have become established for marine and aviation structures. Whilst the same is true of steel fabrications, the close arrays required in this example would render the making and inspection of welds very difficult. Consequently, GRP costs could be lower, since moulding of even complex shapes is relatively inexpensive.

The specific energy absorption figures in Table 2 show that a GRP absorber could be considerably lighter than steel, and therefore easier to handle. The longevity of the two options is probably comparable, as long as the GRP is protected from sunlight and moisture by a thin clad and the steel is either stainless or protected against corrosion.

Although the common resins are inflammable, fire retardants or highly fire resistant phenolic resin could be used. Also, experience of fires in GRP minesweepers made from polyester resin shows that thick sections are intrinsically fire resistant. Progress of burn through the thickness is delayed by the glass layers and the high thermal insulation. In contrast, though a steel absorber is of course not combustible, it will conduct heat readily to the flask surface at its contact points.

Welded steel fabrications are difficult to manufacture to an accurate small scale. Also, it is known that impact parameters cannot be guaranteed to scale in structures susceptible to fracture and tearing (Jones, 1984). A further problem is the possible change to brittle fracture behaviour of weldments at low temperatures.

The performance of GRP against some of the above criteria is not well established, but there is evidence that the impact properties are not highly dependent on glass and resin types, glass/resin ratio or temperature (Thornton, 1979 and Thorton et al, 1985). Manufacture is scalable since scaled sizes of glass cloth are available and there is evidence that impact is reasonably scalable (Farley, 1986), though more investigation is required. Unfortunately, however, there appears to be little data available on the effect of impact angle on crush stress of GRP.

TEST PROGRAM

In view of the potential benefits of using GRP as a flask energy absorbing material, a test program has been put in hand to investigate scalability, sensitivity to glass/resin ratio and temperature, and performance in non-axial impact. However, in advance of these, the latter has been identified as the greatest unknown area. A small preliminary test series has therefore been carried out using rings of a typical glass fibre/polyester resin composition in non-axial impact at room temperature.

EXPERIMENTAL PROCEDURE

The proposed GRP energy absorber for angled impacts has to be effective for impact angles between about 20° and 90°. In order to keep the number of preliminary tests to a minimum, but have a representative range of impact attitudes, three different impact orientations of GRP rings onto a flat rigid anvil target were tested. These were at 22°, 50° and 90° between the axis of the GRP ring and the perpendicular to the test anvil. In order to eliminate the complication of rotation during impact, the missiles were designed so that the centre of mass was above the point of impact. This meant that a different steel backing mass for the GRP was required for each impact angle.

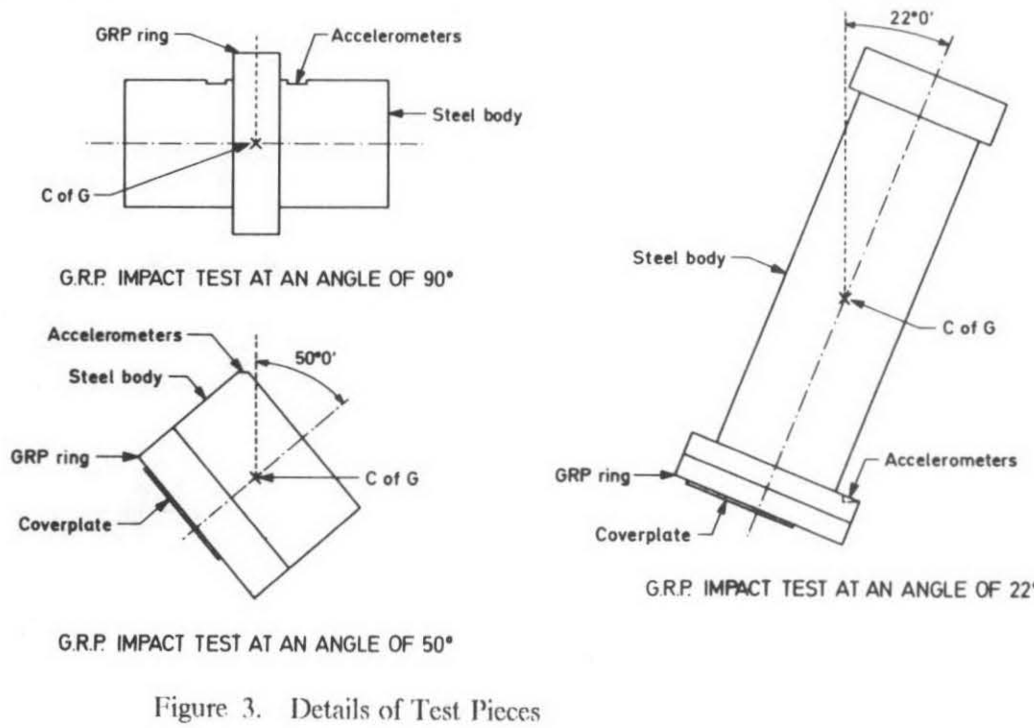

Figure 3. Details of Test Pieces

The nominal outer diameter of the GRP rings was 238mm and the nominal thickness was 35.2mm. The rings were of nominal length 61mm for the 50° impact attitude, 60mm for the 90° and 31mm for the 22° impacts.

For the first test at each attitude a drop height calculated to achieve a crush of 70%, assuming a crush stress of about 70MPa , was used. (The percentage crush is defined as the ratio of the actual crush distance to the crush distance at which the steel backing mass would begin to impact the anvil.) Second tests at 22° and 50° were carried out with increased drop heights estimated to achieve 90% crush, based on the crush stress found in the first tests at these angles. At 90°, there were drops from 18m and from 2m.

The three different designs of test pieces were as shown in Figure 3. All the missiles were cylindrical and had a nominal mass of 60 Kg. The GRP rings were made from cylindrically wound chopped strand glass mat, with the occasional layer of woven mat, and polyester resin.

For each test, two accelerometers were fitted to the missile in order to measure the vertical acceleration-time history. The signal from each accelerometer was low pass filtered at 2 kHz and recorded. Each impact was filmed by high speed camera in order to subsequently find the rebound velocity. Metrology of the GRP ring was undertaken before and after each test.

RESULTS

In each of the tests with an impact angle of 22° or 50° the footprint area on the ring was fairly flat. Crush distances were measured, in a direction perpendicular to the anvil, from the initial contact point of the GRP to the footprint surface.

The material crush stress may be calculated in two different ways. The first uses the equation $\sigma_c = E_a/V$. This method gives a mean value which is effective throughout the impact. The second method assumes that the peak acceleration of the missile occurs when the area of the crushed footprint is the greatest. Equating the inertia force on the missile to the force exerted by the material gives $\sigma_c = m\hat{a}/A$, where $\hat{a}$ is the peak acceleration of the missile and m is its mass. This leads to a crush stress which is appropriate to the end of the impact. Substituting experimental values gives the test results which are summarised in table 3 for 22° and 50° attitudes.

Impact Attitude	22°	22.5°	50°	49°
Drop Height (m)	1.20	2.60	3.55	10.40
Rebound Height (m)	-	0.107	0.066	0.179
Mass (Kg)	62	62	56	56
Peak Acceleration ($m\ s^{-2}$)	3300	5000	5300	8400
Mean Acceleration ($m\ s^{-2}$)	1500	2250	2650	4670
Crush Distance (mm)	7.1	10.5	13.6	25.1
Percentage Crush	54%	78%	50%	94%
Crushed Volume (mm^3)	5100	13100	12800	58500
Area of Footprint (mm^2)	1790	3090	2340	5750
Crush Stress from volume (MPa)	142	116	149	96
Crush Stress from area (MPa)	114	100	127	82

Table 3. Summary of Test Results

Both tests at 50° impact attitude were very successful. Post-test, the rings generally had a truncated appearance, with fairly flat footprint areas. Some delamination could be seen extending through the footprint and a small distance outside. However, this did not lead to detachment of laminations since their hoop integrity was retained in the uncrushed ligaments. Thus, there was no gross failure of the rings or damage to the inner surface, even for the second test, which achieved 94% crush. Figure 4 shows the damage resulting from the 50°, 3.55m drop. Loose debris found after the tests was mostly small well-crushed pieces, with some larger pieces which had apparently been sheared off.

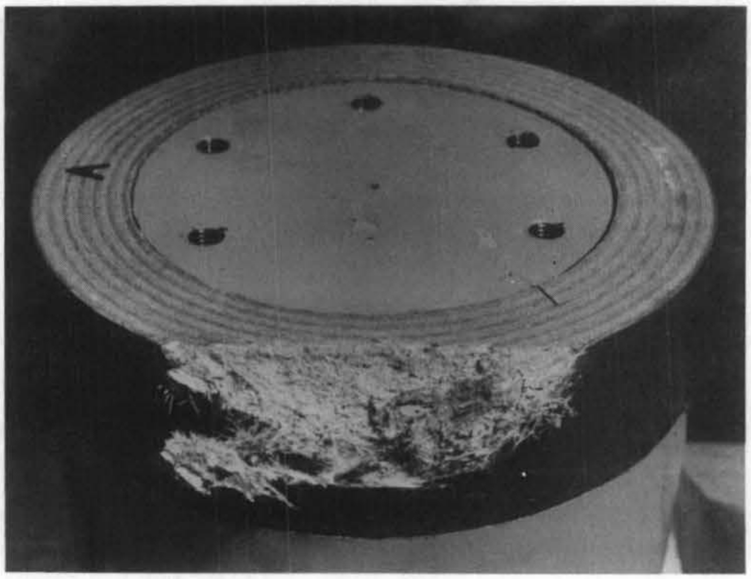

Figure 4. Typical Crush of GRP Test Piece

The rings performed similarly in the 22° tests to the 50° tests. However, delamination in the footprint area extended through to the back face, probably due to the smaller ring thickness. In the second test a few of the outermost laminations failed in the uncrushed ligaments. Again, there was no gross failure of the rings or damage to the inner surface.

The tests with an impact angle of 90° were not as successful. In the drop from 18m, there were premature shear failures right through from the outer to the inner diameter in the impact region. Large fragments of uncrushed material were ejected sideways. The consequent loss of hoop integrity allowed the ring to spring open, with extensive delamination around most of the circumference. The drop from the reduced height of 2 m confirmed that the premature shear failure of the GRP occurs after little energy has been absorbed.

DISCUSSION OF TEST RESULTS

In general, the tests very successfully demonstrated the feasibility of using GRP as a flask energy absorbing material. For impact angles of 22° and 50° the mean crush stresses were towards the higher end of the range given in Table 2, which were based on data from the literature for axially crushed tubes. In all cases, the crush stress at the end of impact (calculated from the area) is smaller than the mean crush stress (calculated from the volume). This is consistent with a falling crush stress versus crush distance curve, due to a lessening of constraint of the crush area. A similar effect would occur in a solid steel absorber. It is a beneficial effect for any absorber in which the contact area increases with crush distance, since it will lower the peak load on the flask.

Results from the lower drop height tests show little variation of crush stress with impact angle, but the higher drop height tests show an 18% fall from 22° to 50°. However, the percentage crush distance increases from 78% to 94% at the same time, which would explain the difference according to the hypothesis above. In general, the crush stress varies surprisingly little from case to case. For design purposes, a figure between the values presented here could be used for a design crush distance of 70%. It is encouraging that crush distances of up to 90% are possible with this material without drastic crush stress changes due to either gross failure or material compaction.

The 90° impact attitude tests all resulted in premature gross failure of the GRP due to shear fracture at 45° to the laminations and subsequent loss of material directly over the impact area. The mode was confirmed by the 90° drop from 2 m. Shear failure right through the ring was noted at this low impact velocity before any ejection of material. The result was very poor energy absorption.

IMPLICATIONS FOR ENERGY ABSORBER DESIGN

The crush stress values found for impact angles of 22° and 50° indicate that this material could be very suitable for the flask application explored earlier. Fine tuning to the required crush loads would only require minor changes to the absorber shape. However, the failure and low energy absorption which occurred at 90° impact angle is clearly undesirable in a flask absorber design. A change to the construction is required which does not detract from the performance in other attitudes. One method could be to alter the shape, while another approach would be to change the lay up of the laminations. Possible solutions are currently being investigated.

CONCLUSIONS

Calculations for a notional flask design and energy absorber geometry show that the crush stress required of the energy absorbing material varies from 11MPa for axial impact to 99MPa for transverse impact. A design solution incorporating GRP and aluminium honeycomb has been proposed. GRP potentially has many advantages over alternative materials, but some key properties have yet to be fully explored.

Preliminary tests have shown that a thick GRP ring, with hoop laminations of chopped strand mat, predictably and progressively absorbs energy when impacted at angles of 22° and 50°. Mean crush stress varies from about 100 MPa to about 150 MPa, and crush stress at the end of impact varies from about 80 MPa to about 130 MPa. From this limited test series, it appears that crush stress falls with increasing crush distance but is little affected by impact angle. Up to 50° crush distances of over 90% are possible without gross failure.

At an impact angle of 90°, premature through-thickness shear failure occurs leading to unacceptably low energy absorption. A design scheme to overcome this difficulty without compromising performance at other impact attitudes is currently being investigated.

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