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ORIGINAL ARTICLE

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Attempts to improve on the V-hull structural design for air-blast loading applications

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Abstract

Mine resistant ambush protected vehicles often use mono-V structures in the design of their hulls for blast protection purposes. These hulls deflect blast waves laterally in the event of a landmine detonation directly beneath the vehicle. Lower internal angles offer greater deflection capability, reducing the impulse transfer to the vehicles, but at the cost of increased ride height. This paper reports results of attempts to improve on V-hull structural designs for air-blast loading applications, where scaled blast tests are performed to evaluate the designs in terms of structural deformation, rupture and impulse transfer characteristics. Structures with double V and W profiles are compared to mono V structures with a 120° internal angle, such that the proposed designs do not increase the ride height. Results showed that the double V-structures limit the central deformation, but some designs have severe deformation at the interface of the central V plate and the shallow base angle structure. W structures seem to be susceptible to rupture at low charge masses There is no single answer to improved blast protection of vehicle hulls, as design choices must be driven by the anticipated threat range, the important performance metrics and other operational considerations.

Keywords

Blast loading, steel V-structures, landmine protection, explosive testing, transient response, plastic deformation, impulse transfer.

1 Introduction

Mine resistant ambush protected (MRAP) vehicles are designed to protect their occupants from harm during anti-vehicular landmine (AVM) incidents. AVMs usually contain 7-12 kg of TNT-equivalent explosive [1], although mines are often double-stacked or triple-stacked to increase their lethality. AVMs are intended to incapacitate or destroy vehicles and kill the occupants. The fireball and blast wave damage the running gear while the shock and impulse imparted to the vehicle damages the crew compartment.

One of the common protective features in MRAP vehicles is the V-hull structure placed underneath the crew compartment. The profile of the steel V-structure is cold formed by bending, as welding was found to weaken the blast protective capability [2]. Research has shown that the V-structure deflects the blast wave laterally, reducing vertical impulse transfer and preventing blast wave interaction with the crew compartment [2-5].

A compromise is required when determining the internal angle of the V-structure. Small internal angles mean a higher centre of gravity and reduced space in the crew compartment [5]. Larger angles are less effective at laterally deflecting the blast load [2-5].

The history of MRAP vehicle development has shown the same trends, with initial vehicles having very sharp internal angles and poor handling but later ones increasing the internal angle to improve vehicle manoeuvrability [6]. For example, the very successful Casspir MRAP vehicle has a single V-hull structure with a larger internal angle than the earlier Hippo Mark I.

This paper reports the results from an experimental investigation into the effects of modifying the geometry of scaled V-hull structures subjected to localised air blast loading. Several designs are proposed and evaluated by comparing the deformation, rupture and impulse transfer characteristics to those of a conventional mono 120° V-structure subjected to the same air-blast loading conditions. The results are compared to previous experimental work on more traditional V-structures at the same scale [2-3, 7]. Some practical considerations for the design of steel V-structures are discussed using the experimental results.

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2 Scaling and design of V-structures

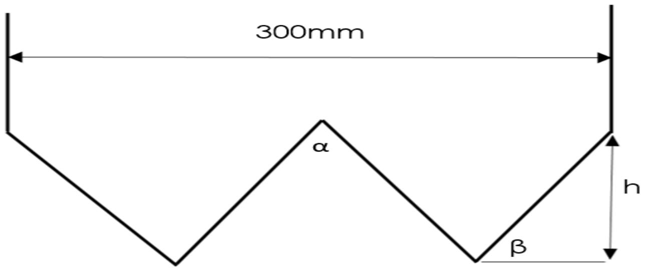
2.1 Scaling approach

Yuen et al [2] used geometrically similar scaling to determine blast test dimensions for V-structures by taking a potential real-life scenario of a TM-57 landmine (diameter 0.316 m) being detonated directly beneath the v-tip of the popular Casspir armoured personnel carrier (width approximately 2.5 m, ground clearance of 0.41 m). This gave a scale factor of 8.33:1 for a 300 mm wide V-structure specimen, meaning that the charge diameter was fixed at 38 mm and a maximum stand-off distance (SOD) of 50 mm. The same approach is used herein, with work on off-centre or buried charge detonations being outside the scope of investigation.

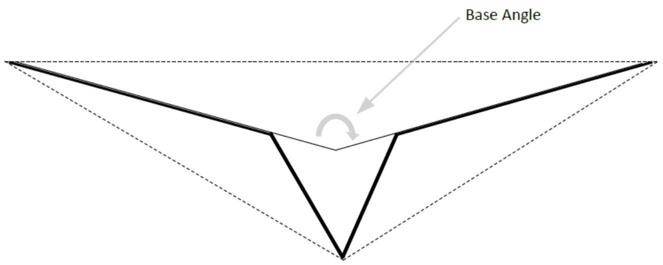
Yuen et al [2] used a SOD of 34 mm and a charge mass range of 5 g to 58 g PE4 which, when scaled up, is beyond the design limit for the Casspir APC (14 kg TNT, which would have given a scaled PE4 equivalent charge mass of 19 g using an equivalence factor of 1.3 and Hopkinson-Cranz scaling). The thickness of the Casspir V-plating was not specified by Yuen et al [2], but the 2 mm thick Domex plates used in their experiments would be equivalent to full-size plates that were 16.7 mm thick. The tip radius of only 4 mm is considered very sharp for sheet metal bending. Yuen et al [2] varied the internal angle, while in this work only designs that fit within the 120° mono-V structural envelope are considered.

2.2 Specimen particulars

In this work, the same nominal width of 300 mm, SOD of 34 mm and charge diameter of 38 mm are used. The tested V-structures were manufactured by bending 2 mm thick Domex 700MC sheet steel to the required shapes. This grade of steel is a hot-rolled, high strength, cold-formed steel with a quasi-static yield stress of 818 MPa. It is used to allow comparison with past work [2-3]. Johnson-Cook model parameters are found in references [2, 8].



(a) the W-structure design



(b) the mono-V120 R0 (sharp-tipped) cross-section profile with a double V-structure profile included as an example in bold

Figure 1 Schematic showing typical design schematics and the mono V120 profile shape

Eight designs were considered, as listed in Table 1. Two designs were mono V-structures with an internal V-angle of 120°, but with different V-tip radii of 4 mm and 32 mm respctively. Two W-shape designs were manufactured with different nominal central angles (α), shown in Figure 1a. Note that when α=120°, the outer inclined surfaces are vertical (so β=0°). Four designs were double V-structures, with a a sharp (lower angle) central V-section atop a shallow base angle.

Since the aim of the protective structures is to provide at least equivalent protection without influence the vehicle ground clearance, all the designs had a maximum height of no more than the baseline 120° sharp-tipped mono V-structure shown in Figure 1b. For illustrative purposes, one of the double V profiles is shown to fit inside the mono V120 profile.

Table 1 Description of the different protective structure designs

Type	**Basic shape**	Description
Mono V120 R4	Single V	120°, 4 mm tip radius
Mono V120 R32	Single V	120°, 32 mm tip radius
DBL V150-90	Double V	150° base angle, 90° central V-angle, 4 mm bend radius
DBL V150-75	Double V	150° base angle, 75° central V-angle, 4 mm bend radius
DBL V150-60	Double V	150° base angle, 60° central V-angle, 4 mm bend radius
DBL V165-60	Double V	165° base angle, 60° central V-angle, 4 mm bend radius
Mono W80	Single W	α = 80°, h = 86.6 mm, β = 48.4°
Mono W120	Single W	α = 120°, h = 86.6 mm, β = 0°

3 Blast test method

3.1 Experimental arrangement

Localised air-blast loading was created by detonating 38 mm diameter plastic explosive PE4 discs, in air, situated at the midpoint of the V-ridge at a constant 34 mm stand-off distance (SOD) using a polystyrene bridge arrangement. The PE4 discs were detonated using an electrical detonator placed at the diametric centre of the charge, in contact with the rear surface. The polystyrene bridge is assumed to have minimal influence on the ensuing blast wave development, as the polystyrene is not between the charge surface and the structure of interest.

The test arrangement is shown in the photograph in Figure 2. The SOD and charge diameter were determined from the scaling approach described in section 2. The SOD was dependent upon the ground clearance, as previously described. However, for the W-structures, clearance heights of 34 mm and 50 mm were used, rather than defining a SOD, as the central part of the structure was much further away from the charge mass.

The charge mass was varied between 10 g and 50 g PE4 by varying the height of the explosive disc. The pendulum displacement was measured using a wall-mounted laser displacement sensor. The impulse transferred to the plates was estimated from the maximum swing of the pendulum using single degree of freedom analysis. The panels were scanned after testing to obtain a three-dimensional plot of the plate surface for comparing the deformation and failure.

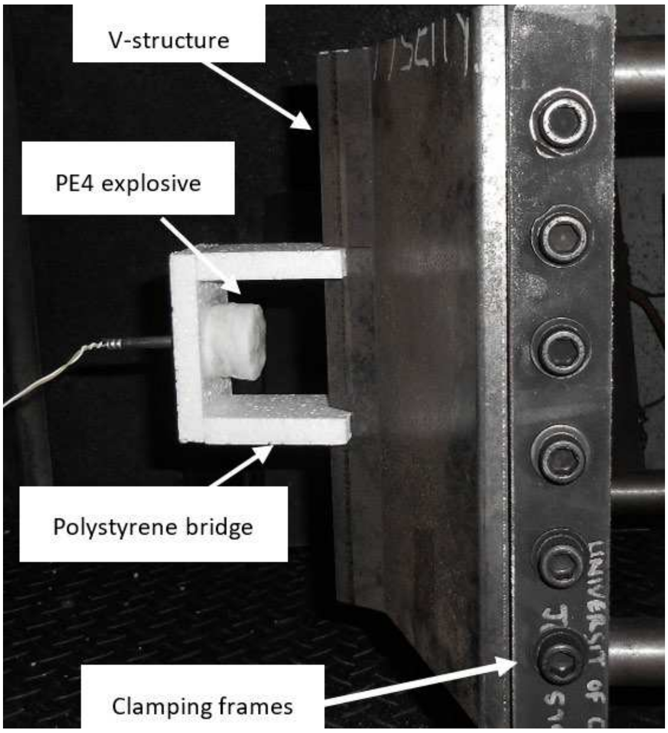


Figure 2 Photograph showing a side view of a double V-structure, ready for blast testing, and the vertical clamping of the straight sides. Source: Andrew Curry/University of Cape Town

3.2 Clamp frame redesign

Computational modelling of the clamp frame design used in reference [2] showed that it produced impulse recirculation along its clamped edge that would not be representative of a real MRAP vehicle hull [7]. Thus, the clamping system was redesigned such that the clamps were attached along the straight vertical edges, as shown in Figure 2. The clamped areas on the V-plates were machined with twelve (six per side), 12 mm diameter, holes to facilitate the mounting and clamping of the plates to the pendulum.

3.3 Transient response measurements

A small number of tests on the mono V120-R32 structures employed stereo-imaging techniques for determining the transient displacement of the central region of the V-structure. For these tests, the central region of the rear surface of the V-structure was prepared with a speckle pattern of random black speckles on a white painted background, shown in Figure 3.

Figure 3 Photograph showing speckle pattern on rear surface of a V120 R32 structure. Source: Vinay Shekhar/University of Cape Town

Two high speed cameras were mounted inside the pendulum and were used to film the ridge of the V-structure as it deformed during the blast tests. The cameras were triggered at detonation using a break-wire circuit. The response of the structure was filmed at a frame rate of 30 000 fps with an exposure time of 31 µs. Additional LED lights were used to illuminate the back surface for the short exposure time. These tests were performed at low charge masses (below 20g) to ensure that the cameras were well protected from the blast wave and fireball.

After testing, the camera images were processed using the Dantec Dynamics Istra 4D Digital Image Correlation (DIC) software package to determine the transient deformation at the centre of the structure. Since the V-structure had inclined surfaces, it was not possible to track the deformation across the structure due to the limited depth of field of the cameras. Careful pre-test calibration enabled tracking of the movement of the speckle pattern (using a correlation algorithm) to minimise the errors associated with DIC (estimated to be approximately 1.5 mm on the peak displacement in work by Curry and Langdon [9]).

4 Results and discussion

4.1 Deformation response

All the structures, regardless of design type, exhibited large plastic deformation. Photographs of some typical deformed V-structures are shown in Figures 4 to 7. As expected, higher charges masses caused greater amounts of damage with an increase in the total deformed area and higher mid-point displacements.

4.1.1 Mono-V structures

For the mono-V structures, the inclined faces either side of the ridge plastically deformed. The V-ridge, and the plate material immediately around it, plastically deformed and the plates pinched on the underside, as shown in Figure 4. The 4 mm tip radius structures exhibited pinching of the inclined faces while this was not observed in any of the 32 mm radius mono 120° V-structures. Figure 5 shows a photograph of a typical blast tested mono V120 R32 structure. The ridge exhibited significantly more deformation than its sharper tip radius counterpart. The ridge deformed inward as the 32 mm bend radius was far less rigid.

The deformation-time history of the central point on the rear surface of three 32 mm tip radius mono 120° V-structures are shown in Figure 8. The first 8 ms of displacement data is plotted against time. Unfortunately, motion blur in the first two frames means the very beginning of the curve is missing making it impossible to infer the initial velocity field across the structure, as used by Rigby et al [10] to infer the impulse distribution across blast-loaded flat structures. There are also small gaps in the post-peak response data, caused by debris which obscured the camera images for short periods of the footage. However, despite these imperfections in the data, the general characteristics of the response were still evident.

Figure 4 Photograph showing a V120 R4 structure (rear view), subjected to a 19g detonation. Source: Andrew Curry/University of Cape Town

Figure 5 Photograph showing a blast tested 32mm tip radius mono 120° V-structure (blasted side), 20 g. Source: Vinay Shekhar/University of Cape Town

Figure 6 Photograph showing a blast tested double 150-75 V-structure (blasted side), tested at 50g. Source: Aashir Siddiqui/University of Cape Town

Figure 7 Photograph showing a blast tested double 150-90 V-structure (rear side), tested at 35g. Source: Aashir Siddiqui /University of Cape Town

For both charge masses, there is a rapid initial increase in displacement, reaching a peak displacement after approximately 1 ms. The structures then entered an elastic rebound phase, where the displacement oscillated about a lower permanent displacement. Permanent displacements were approximately three to four plate thicknesses lower that the peak transient displacement. As expected, the 15 g detonations produced higher peak displacements than the 10 g detonation. It is encouraging to note the good repeatability observed from the two 15 g detonations.

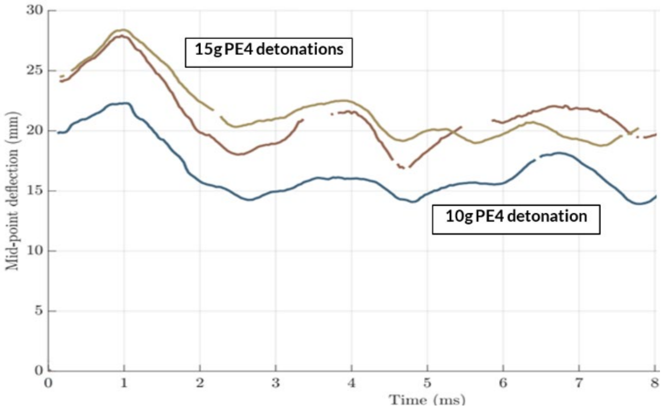


Figure 8 Transient mid-point displacement-time histories obtained from DIC analysis of blast test footage for 10 g and 15 g detonations on V120 R32 structures

4.1.2 Double-V structures

Within a plate type, the extent of the deformation increased with increasing charge mass, as expected. Figure 6 shows the blasted side of a 150-75 panel subjected to a 50 g PE4 detonation. The ridge directly below the charge location deformed and the plate material either side of the ridge bend deformed and buckled. Pinching failure was also apparent in these structures, where the plate sides of the V-ridge deformed inwards and made contact, shown in the photograph of the 150-90 double V-structure in Figure 7. These are similar to the deformation modes observed in mono V120 structures in the central region of the structure. The differences in deformation pattern were apparent in the base angle/central V transition region, which is difficult to observe from the photographs but is evident from comparing the deformation profile plots of the mono and double V-structures in figures 9-10.

The shallow base angle plate deformed in the direction of the applied blast loading. The extent of the base angle deformation was more severe than the movement of the central V-tip for the lower central V-angles, as illustrated in Figure 9 which shows a graph of section height versus plate width compared with the original double-V profile for the 150-60 double V-structure. The deviation from the dotted line is the deformation of the structure. It is evident from Figure 9 that the deformation at the intersection of the base and central V angles is the most severe. The change in profile shape at 50 g would indicate that the V-structure would impinge on the crew compartment floor if it was located directly above the V-hull in an MRAP.

A similar graph for the 4 mm tip radius mono 120° V-structures after blast testing is shown in Figure 10. Even though the mono V-structures exhibited larger deformations overall, they do not exhibit this worrying tendency to impede on the flooring as the deformed region was in the centre of the structure which is located at the greatest distance from the crew compartment. The 150-90 double V-structures also exhibited relatively little movement of the shallow base angle plate, attributed to the lower resistance to deformation of the greater central V-angle compared to the other double V-structures.

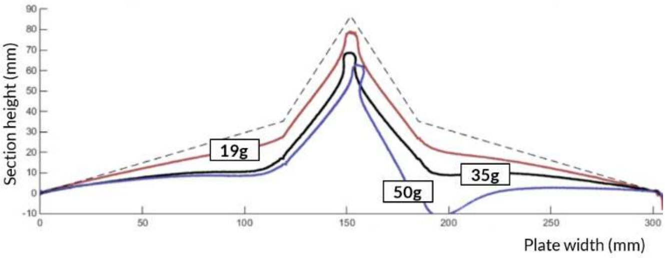


Figure 9 Graph of height versus plate width for selected 150-60 double V-structures after blast testing (dotted line represents the undeformed profile)

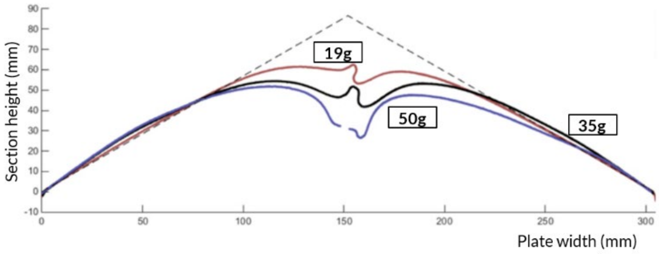


Figure 10 Graph of height versus plate width for selected 4 mm tip radius mono 120° V-structures after blast testing (dotted line represents undeformed profile)

4.1.3 W structures

The W80 structures exhibited tearing failures in the charge mass range used for the V120 and double V tests, so the charge mass range was reduced to 8-10 g PE4, and two clearance heights of 34 mm and 50 mm were used. The W80 structures exhibited small amounts of plastic deformation at 8 g. Increasing the central angle to 120° resulted in a more damage tolerant structure, with only plastic deformation observed as the damage mode up to 10 g PE4 and a clearance height of 34 mm. The internal inclined plate faces bulged towards the apex at 10 g PE4 while ridge displacements of approximately 4 mm were measured.

4.2 Rupture failure of structures

Partial tearing failures were noted at higher charge masses in some plate types, as shown in the photographs in Figures 11 to 13. The deformation profile and location of first rupture varied according to specimen geometry. The V120 R4 structures ruptured along the ridge-line, as shown in Figure 11. Thinning and tearing occurred along the edge of the ridge, as the ridge itself was strain hardened during the sheet metal bending process.

Figure 11 Photograph of ruptured V120 R4 structure (blasted side) tested at 50g. Andrew Curry/University of Cape Town.

The double V-structures exhibited rupture in one of two locations, depending upon the combination of base angle and central V-angle. Tearing occurred along the central ridge (similar to the mono V-structures) or near the bend between the ridge and the base angle plates, as shown in Figure 12. Pinching failure, where the inclined plates deformed inwards and made contact on the rear surface, is also evident in Figure 12. Tearing increased with increasing charge mass, as expected.

The W80 structures exhibited large amounts of tearing along the central bend, as shown in Figure 13, at the low charge mass of 10 g PE4. Petalling was observed in the 19 g PE4 detonation test. Rupture was still a prevalent failure mode at 10 g PE4 when the clearance height was increased to 50 mm. The W120 structures exhibited small amounts of tearing along the central ridge, but this was far less extensive than that observed for the 80° central angle tests.

Figure 12 Photograph of ruptured V150-60 structure (rear side) tested at 50 g showing rupture along the central V/base plate interface bend. Andrew Curry/University of Cape Town.

g at a clearance height of 34 mm. Christopher Murray/University of Cape Town.

4.3 Impulse transfer

In general, there was a trend of increasing impulse transfer with increasing charge mass within a design type, as might be expected from previous work [2-3, 7]. The impulses measured in the current experiments were approximately 10% lower than those reported by Yuen et al [2] due to improvements in the clamp frame design in the present work. The new clamp design reduced clearing effects around the raised clamp edges by moving the clamp to the vertical straight edges which do not impede the blast wave flow [7].

The impulses transferred to the mono V120 structures were similar in the 19-20 g detonations, regardless of bend radius, indicating that there was little difference between the global impulse transfer characteristics of the R4 and R32 mm tip radii structures. This is consistent with the predictions from rigid V-structure numerical modelling presented by Langdon and Shekhar [7].

A column graph of impulse versus explosive charge mass is shown in Figure 14 for the double V-structures and the mono V120 R4 structure. These could be directly compared for charge masses of 19 g, 35 g and 50 g, whereas the other structures were tested in a lower charge mass range. For the mono-V configurations, past work [2, 7] suggests that the internal V-angle is the dominant factor in determining the impulse transfer characteristics when SOD and charge mass are kept constant. If the same influence were present in the double V-structures, the impulses for the structures with the same central internal angle (that is, 150-60 and 165-60) would be indistinguishable, and the double V-structures with the 60° internal angle would exhibit the lowest impulse transfer of the double V-structures. However, neither of these trends are evident herein. The dominance of V-tip internal angle in determining impulse transfer is less obvious.

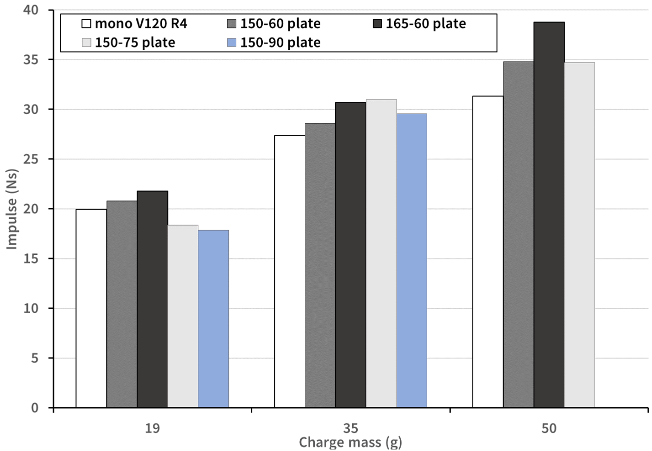


Figure 14 Graph of impulse transferred to the pendulum during the blast tests for the mono V120 R4 and double V-structure tests

For a low charge mass (19 g), the 165-60 and 150-60 configurations exhibited higher impulses that the mono V120 R4 baseline structure while the 150-75 and 150-90 structures seem to offer improvement (that is, lower impulse transfer) in performance. However, at 35 g and 50 g, all the double V-structures transfer higher impulses, with increases ranging from 15-30%. The 165-60 was the worst performing design in terms of impulse transfer and was also the heaviest of the double V-structures.

By assuming a linear relationship between impulse and charge mass, the impulse transferred to a W-structure at 19 g PE4 was estimated from the 10 g PE4 detonation. The impulse transfer is estimated to be 21 Ns and 28 Ns for the W80 and W120 structures respectively, which are both higher that the V120 R4 structures. It must be noted that this finding is somewhat tenuous as this linear assumption may not be accurate. No linear impulse-charge mass relationship has been proven for this type of structure, although it has been demonstrated for flat and V structures [2-3, 7, 9]. Additionally, the W structures may rupture in a 19 g PE4 detonation (as rupture of the W80 structures was observed at 10 g). Rupture would allow ingress of the blast pressure wave and explosive detonation products into the vehicle, which in turn may affect the impulse transfer to the vehicle.

It should also be noted that the results presented in Figure 14 are global impulse values, smeared across the structures, and there may be significant differences in the spatial distribution of impulse that could not be measured in the experiments. Despite this limitation, from an applications perspective, global impulse transfer to the MRAP vehicle hull is an important design consideration. The mono V120° structure outperforms the other designs based on impulse transfer characteristics.

5 Application to MRAP hull design

Applying the findings of this work to the design of realistic V-hull protective systems is challenging as the performance metrics (and their relative importance) vary according to (a) the mission of a particular MRAP, (b) the range of threats it may encounter and (c) the probability of risk to its operation. To add to the complexity, even when not considering the field of operation, the geometric changes in the double V-structures and W structures affect both the blast loading transferred to the structure and the deformation or damage tolerance of the structure.

Ultimately, mono V-structure MRAP hull design history has shown that operational constraints must be of primary importance during selection of underbelly protection systems [6]. A 45° internal angle would result in the lowest impulse transfer and the lowest deformation but would require a very high ground clearance, and so mono V-structures usually have internal angles in the 105-120° range, such as the Casspir [6-7]. In the new designs considered herein, ground clearance was removed as a factor by ensuring all designs fitted into the same envelope as the mono 120° V-structure baseline design.

Thus, the 150-60 design does not automatically have the lowest impulse transfer because the 60° V section extended across a smaller width of the plate than the double V-structures with higher central V-tip internal angles. The change in shallow angle also affects the extent of the plate covered by the central V-tip angle. This leads to a complex interplay between the internal angle and shallow angle effects on impulse transfer and deformation in double V-structures. The W-structures offer no improvement over the double V and mono V120 designs.

Table 2 shows a range of potential damage and impulse transfer performance metrics and their values obtained from the experiments on each design concept (values are rounded to the nearest gram, Newton-second or millimetre). From the experimental results herein, it is evident that there are significant differences in the performance characteristics of the eight designs, and that there is no clear “best” design for all performance parameters.

Evaluation of the designs relies heavily on the performance metric selected. For example, if limiting the mid-point deflection of the hull is important, then the double V150-60 and 165-60 designs would be good choices, while the mono 120° V structure would perform poorly. If limiting base angle deformation is critical (which it could be in order to prevent impingement of the hull onto the crew compartment flooring), then the mono V120 and the double V150-90 designs would be good options.

If preventing rupture of the structure is deemed critical to prevent pressure waves and harmful gases entering either the crew compartment or damaging the internally mounted equipment, then the mono V120, double V150-90 and V165-60 appear to show promise. Additionally, it will be likely that the location of first tearing may be important, particularly if the hull is used to store or protect items other than the floorplate of the crew compartment. The W structures showed little resistance to tearing, making them poor options. Ease of repair may also become a factor if the tearing location can be predicted, favouring designs where the tearing location can be easily accessed from the underside of the vehicle and where the ingress of detonation products will have done little other damage to the vehicle or its occupants.

When impulse transfer is the principal consideration, then the mono V120 plate is the best option, with its advantage extended at higher charge masses. Decreasing vertical impulse transfer stops the vehicle from being lifted off the ground. This limits injuries to the occupants who may be thrown around inside the crew compartment. The 165-60 design would be the worst choice. If mass were a critical factor, the 27% extra mass required for the 165-60 design would limit its usage especially given its poor impulse transfer characteristics. The mass penalty would influence the fuel efficiency, range, manoeuvrability and speed of the MRAP vehicle.

Table 2 Performance measures for test structures

Type	**Rupture threshold (g)**	**Impulse at 35g**	**Mid-point displacement (mm) at 35g**	**Displacement of base angle plate (mm) at 35 g**
Mono V120 R4	50	27	31	N/A
Mono V120 R32	Not known			N/A
DBL V150-90	35	30	9 (partially torn)	4
DBL V150-75	Over 50		10	18
DBL V150-60	35	29	7	23
DBL V165-60	Over 50	31	3	19
Mono W80*	10	Not tested	Ruptured at 10g	Ruptured
Mono W120*	Not known	Not tested	Not tested	Not tested

*For a clearance height/SOD of 34 mm

As demonstrated above, different performance criteria would necessitate different design choices by a blast protection engineer tasked with protecting a MRAP vehicle. The weighting given to each performance metric will depend upon the anticipated threat scenarios and the mission of the MRAP vehicle. The designer must be given accurate information about the likely loading scenarios (perhaps using a risk-based approach to the threats, rather than a deterministic single threat scenario) to be faced by the MRAP vehicle and the critical threats to passenger safety. The battlefield and the tactics employed by terrorists and/or insurgents are continuously evolving, so it may not be possible to define these requirements exactly. The results presented herein are intended to give a designer some indication of possible performance measures and to point to the danger of relying upon only one parameter, with the intention of encouraging stochastic approaches to blast performance assessments of MRAPs.

6 Concluding Comments

Plastic deformation and rupture were the dominant failure modes observed in the mono V, double V and mono W structures subjected to localised air-blast loading, with the location of deformation and tearing dependent upon the charge location and structural geometry. The designs tested herein have attempted to improve on the baseline mono V120 structure, as this is the case most like that employed in full scale MRAPs in service. The work demonstrates that it is difficult to categorically show blast protection improvements, as it strongly depends on the performance metric(s) used and the anticipated in-service operational needs and threats.

With that proviso, the double V-structures offer some potential improvements if limiting central ridge defection or improving the rupture threshold charge mass is important, but not if impulse transfer or deformation away from the centre are more critical. The W-structures seem to offer little benefit. The W80 structure was especially prone to large amounts of rupture along the central bend, although the wider angle W120 structure was better and may be worth further investigation. Some designs, such as the double V165-60 have a mass penalty, which would form part of the consideration in transportation applications as it may affect vehicle top speed, range and environmental impact.

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