DEFORMATION AND FAILURE IN EXPLOSIVELY LOADED STEEL STRUCTURES

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ABSTRACT

Over the period 1993-1996 the Naval Platform Survivability Section of the Australian Department of Defence, Defence Science and Technology Organisation conducted a series of tests which aimed to study the effects of internal explosive loading on welded steel structures with particular emphasis on dynamic response and failure mechanisms in this type of construction. These tests were performed on a combination of different 1m^3 steel boxes[1-3], full scale models of ship compartments[4] and eventually live fire tests on the decommissioned Royal Australian Navy, Destroyer Escort HMAS Derwent[5] with the overall objective of improving the survivability of current and future RAN warship to explosive warhead threats.

Beyond the requirements of sound ship design for normal operational activities, the design of ship structures to survive explosive threat effects requires detailed knowledge of the complex deformation and failure mechanisms associated with this dynamic loading regime. An understanding of these mechanisms necessitates a study of both cause; the explosive loading of the ship structure, and effect; the structures' response in terms of both deformation and failure. Without this basic understanding of the failure processes a successful programme for the design of ships with enhanced structural survivability is not achievable.

A common feature observed in this series of trials was the regular failure of bulkheads at their deck and deckhead boundaries. It was evident that an understanding of both the explosive loading, ie blast physics, and consequent structural response, ie deformation and failure, of these boundaries is an important part of possible damage mitigation in ship structures. Based on these observations an experimental test apparatus has been designed which aims to facilitate the study of the relative performance of alternate bulkhead boundary attachment designs as well as construction techniques and procedures. This paper describes both the preliminary experimental outcomes and predicted deformation results obtained using the LSDYNA3D finite element analysis codes.

1. INTRODUCTION

Previous research [1,2,3] using fully welded steel plate cubicles, internally loaded with spherical explosive charges, showed that structural deformation and consequent failure is highly dependent on the detonation position of the explosive within the structure. For the near field case: charge positioned at less than two charge diameters from cubicle walls, the walls ruptured almost instantaneously and this often initiated wall boundary attachment failure(s). Similarly, for the far field case: explosive charge greater than two charge diameters from the cubicle walls, structural failure always occurred at the boundary edge attachments. In addition, high speed photographic recordings showed that panel boundary edge failures were initiated in the first few milliseconds after explosive loading and this could only have resulted from a combination of loading due to intense 2D and 3D corner shock pressure amplification and the consequent plate through-thickness shear failure at the boundary edge attachment hinge point of the panel walls.

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Subsequent internal explosive blast experiments [4] were conducted on two, full scale, steel construction, ship compartment models. From these preliminary trials, as well as the follow-on full scale ship trials [5], it was shown that full scale ship structures showed similar bulkhead deformation, failure processes and failure mode characteristics to those observed in the test cubicles. These tests further reinforced the requirement that for accurate modelling and consequent prediction of the response of ship structures to dynamic explosive blast loading, it is necessary to fully understand both the physics of the blast loading process, and the resulting structural deformation response and failure of the bulkhead boundary attachments. In addition, since the major transfer of explosive blast pressure from the primary detonation compartment to its neighbours requires the failure of one or more of these primary bulkheads, decks, or their included doors and hatches, the understanding of the primary compartment loading, deformation and failure processes is the cornerstone of any confident prediction/simulation methodology.

Ritzel [6] has shown that blast pressure loads in 2D and 3D corners are greatly enhanced due to strong compound reflections which can easily amplify the incident peak pressure and impulse by an order of magnitude. Since the corners are often also weak regions of the overall structure this load enhancement is undoubtedly a contributing factor to the observe panel edge failure. These strong compound reflections often occur due to the symmetrical nature of the compartment and in the presence of weak walls (below critical thickness or in the presence of inherent, panel boundary joint weaknesses) can be sufficiently large to produce catastrophic edge failure.

Although it is obvious that relatively weak boundary panels will fail in preference to stronger ones, the development of boundary panel failure criteria and their application to failure prediction models for real, relatively complex ship structures is fraught with difficulties. These difficulties include: structural and material inhomogeneities, variation of dynamic pressure loading due to interference of ship compartment equipment and fittings, structural weaknesses introduced during ship construction or after modifications, as well as discrepancies between construction drawings and actual ship dimensions. Many of these discrepancies are impossible to quantify, however, testing and simulation of simple compartment structures and identification of the causes of premature blast pressure related failure may provide design rules which will improve their overall survivability.

The current series of internal explosive blast trials on the experimental bulkhead attachment test rig, for which the panel steel composition, properties and dimensions as well as construction methodology were accurately known and carefully controlled a priori, provided a controlled experimental basis for the development of an understanding of structural response and failure in welded steel structures. These results could also be used to assess the predictive accuracy of blast pressure and structural response computer codes. Although current finite-element computer codes are capable of closely estimating elastic and gross plastic deformation, it is generally unrealistic and inappropriate to apply these codes to an entire ship. However, when such codes are applied to simple, well defined scenarios, they are invaluable for the insight they provide into basic material deformation and failure mechanisms.

This paper describes the preliminary experimental results from a series of internal explosive blast trials on a bulkhead attachment test rig and the comparative results obtained by a range of state of the art blast prediction and finite element analysis computer programs.

2. EXPERIMENTAL

Several trials were conducted during the development of the bulkhead attachment test rig. The singular aim of this development was to design a small scale, inexpensive, rectangular welded steel plate test rig containing a fitted test panel, which both preferentially and consistently failed at a particular explosive charge level and showed the type of boundary attachment failures observed in full scale ship structures.

The first series of experiments were performed on a fabricated, free standing six sided mild steel box with the enclosed portion of the test rig having nominal dimensions of 1m x 1m x 1m. Two 5mm thick target panels were positioned at opposing ends of the box while all other panels were constructed from 8 mm steel plate, Figure 1a, 1b. The boxes were constructed using high quality manual arc welding techniques along all internal and external connecting edges of the 8mm panels and for one 5mm target panel. Fitting of the last 5mm target panel was achieved using a 100mm frame surround of 5mm steel doubly welded inside the test rig at the second target panel position, Figures 1b, 1c. The final 5mm target panel was then fitted inside this frame with a single external deep penetration weld to the frame surround. A 115 mm diameter hole was cut in the top of each test rig for explosive charge placement. Pressure gauges, PCB Model 109A piezoelectric type, were fitted to the centre of one 8mm panel, the corner of two intersecting 8mm panels (2D corner) and the intersection of three panels (3D corner). In each test an uncased spherical Pentolite explosive charge was centrally located and detonated. Explosive charge sizes used were 500g, 750g and 1000g.

To identify the critical panel failure thickness a second series of tests used the identical test rig construction as the first series but with substitution of 4mm, 3mm and 2.5mm thick plates for the 5mm target panels. The target panels for any one test were of identical thickness and for this series explosive charge sizes were all 1000g.

For the third series, the test rig utilised 3mm thick target panels exclusively with 1000g spherical Pentolite explosive charges. Pressure gauge types and locations were identical to those used in Series 1. Although extensive checks were made to minimise explosive charge and test rig welding/construction variations for all the reported tests, this series of experiments was designed specifically to identify test reproducability. With all three series, three sides of the rig were painted flat white and marked with a 100mm black grid. These grid markings were used for hig speed photography and to assist the post trial rig deformation analysis.

To quantify the venting effect of the 115mm penetration used for explosive charge placement one test was performed with the penetration sealed with a bolt-on plate after placement of the explosive charge and the pressure/time measurements compared with the unsealed boxes.

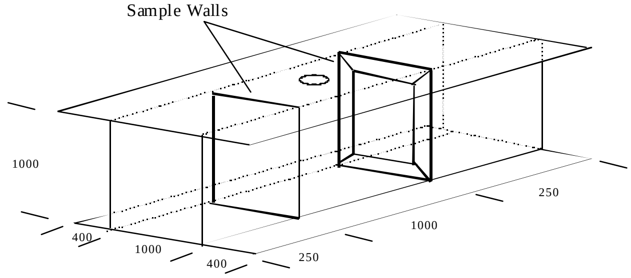

Figure 1a. Schematic of the blast test rig showing general dimensions and sample panel arrangement.

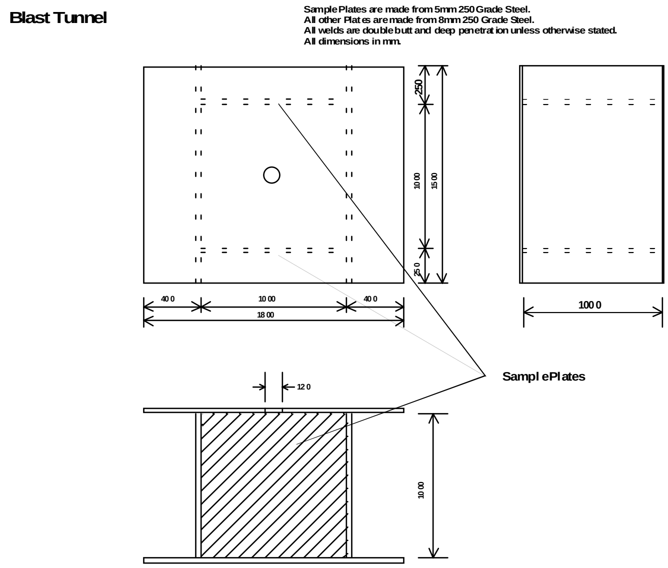

Figure 1b. Construction details of the blast test rig.

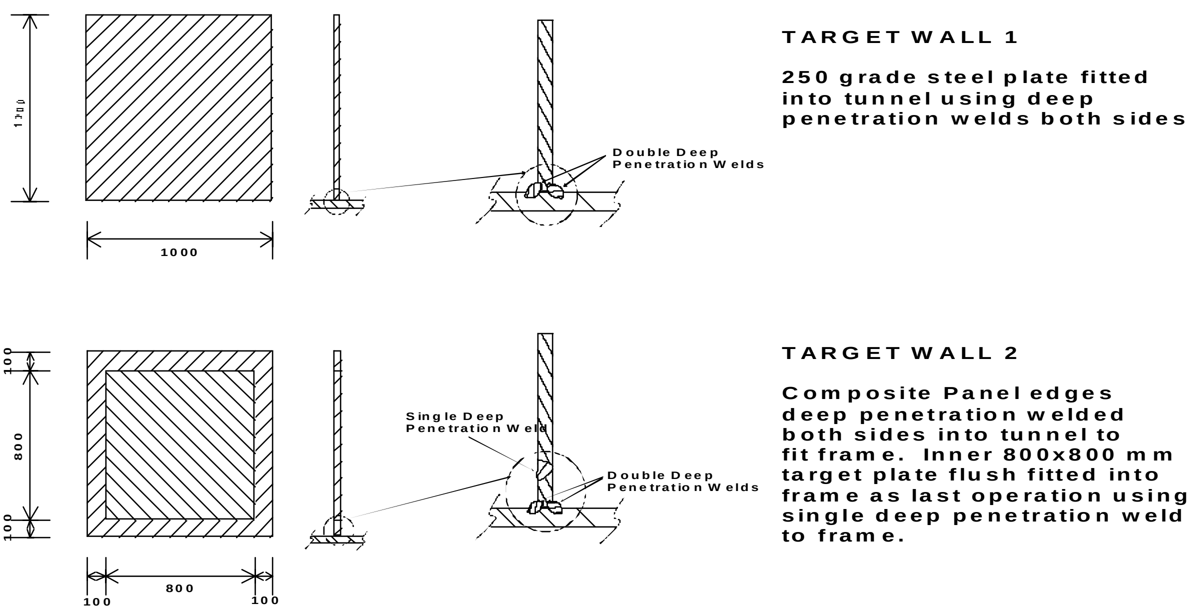

Figure 1c. Test panel construction and fitment details.

Finite element modelling and analysis were performed using the LSDYNA3D [7] suite of finite element analysis (FEA) codes running on a Silicon Graphics Indigo computer work station. Due to the symmetry of the problem it was only necessary to model one eighth of the test rig, hence reducing the CPU run time. The panel material type used was Kinematic/Isotropic Elastic-Plastic with properties shown in Table 1.

Table 1. Test Rig Steel Properties.

Property	Quantity
Young's Modulus E	210 GPa
Poisson's Ratio v	0.3
Yield Stress σ_y	270 MPa
Tangent Modulus E_t	50 MPa
Hardening Parameter β	1.0

For each simulation run, internal panel pressure/time loading data was generated using the Combustion Dynamic IFSAS Blast Work Station program RAYTRACER [8]. RAYTRACER data is calculated using a 'source' and 'image' technique where an empirical free-field explosive 'source' profile is used to compute the pressure-time history for the incident shock wave. As the modelled explosive is detonated, a spherical blast wave is produced and this wave interacts and reflects from 'rigid' walls. Using a combination of ray tracing principles to determine a ray path, and non linear acoustics addition rules to sum contributions of all incoming pressure waves, a pressure/time loading profile was calculated for a number of pre-defined wall locations. All loading profiles were truncated to zero load after three milliseconds and it was assumed that the magnitude of the pressure loading was not significantly affected by box deformation during the structural response. These pressure time loads were applied to the panel faces of the LSDYNA3D test rig model and the simulation run to 20 msec with dimensional output being compared with measured test rig panel deformations.

3. RESULTS AND DISCUSSION

3.1 Series 1

The first stage of the experimental test series involved varying the explosive charge size from 500g to 1000g. For these charge sizes the test rigs were observed to plastically deform without any panel failure. Figure 2 shows a typical test rig after testing with a 1000g Pentolite charge. The experimental deformation of the 5mm sample panels closely followed the results observed on all faces of the earlier cubicle trials [1,2,3], with reduced maximum deformation in the surround panels due to their increased thickness and stiffness: a design feature included to more closely simulate the inherent ship compartment deck/deckhead stiffness.

In earlier experiments [1,2,3], high speed cinematography was used to study the panel deformation sequence. These recordings showed that after explosive detonation the test panels displaced uniformly outward and produced two types of plastic hinge, (a) an outwards plastic hinge fixed at the panel to surround edges and (b) a hinge moving away from the panel edges towards the panel centre. As the deformation continued, the panel edges were pulled inwards due to the overall membrane tensile pull within the panels. Through the inherent orthogonal stiffness of the 3D corners little deformation occurs in this region resulting in an adjacent deformed region of high curvature and strain situated approximately $^{1}/_{8}$th of the panel edge length from the corners.

Figure 2. Deformation of test rig and 5mm test panel for 1000g Pentolite Charge.

Although high speed cinematography was not utilised in this series of experiments it can be assumed that the structural deformation processes were similar to that observed previously since the final overall test panel shape and panel edge hinge characteristics compared favourably. As with earlier cubicle tests the occurrence of hinge lines was observed in all the test panels. As the explosive charge and hence loading conditions were increased, these hinge lines became sharper and more prominent as did the region of high curvature/strain observed adjacent to the 3D corners. Of particular interest in these tests was the development of buckling along the extremities of the panel overhang, resulting from the complex differential deformation of the relatively unrestrained overhang regions and the central box structure, Figure 2. Measurements showed that as the centre of the test rig panels displaced outwards the 3D corners moved towards the geometric centre of the test rig.

A typical result of test rig deformation for an LSDYNA3D FEA simulation of a 1000g charge test is shown in Figure 3 for comparison with the experimental results of Figure 2. The FEA test rig simulation is seen to closely follow the general features of the experimental test rig deformation, including the development of the unsupported edge buckling. Comparisons of measured experimental and predicted test panel deformation showed excellent correspondence. These FEA simulations also highlight the development of high effective plastic strain levels in the panel edge hinge regions as well as extremely high concentrated strain levels adjacent to the 3D corner positions, Figure 3. With increasing explosive charge size the deformation, ie degree of curvature, in the simulated panel hinge and 3D corner regions increased dramatically mimicking the level of measured experimental curvature in these positions.

As observed in earlier cubicle tests [1,2,3], boundary hinge formation is a critical step in the panel failure process and above a critical loading level edge rupture was observed to initiate in these high curvature/strain regions. This close association between the observed high strain regions and the occurrence of panel edge failure indicates the necessity to develop FEA failure models which will allow the realistic prediction of panel edge failure in this type of structure.

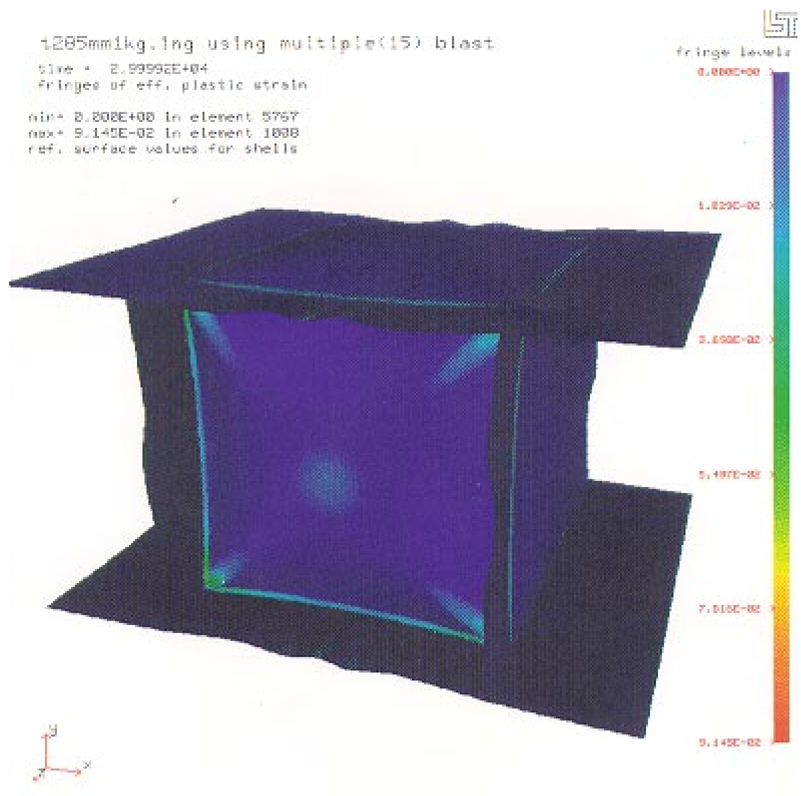

Figure 3. LSDYNA3D simulation of test rig with 5mm test panels for1 kg Pentolite Charge.

3.2 Series 2

The explosive loading conditions used in Series 1 were insufficient to initiate panel failure and rather than increasing the charge size it was decided to try to initiate failure by reducing target panel thickness. Accordingly, for this series, tests were performed using 2.5mm, 3mm, 4mm test panels while maintaining the other 8mm rig panel dimensions. For each of these tests the explosive charge size was 1000g.

Failure did not occur in the test with the 4mm test panels, Figure 4, although the overall deformation increased over that shown by the 5mm sample panel tests with the equivalent explosive charge. In the 3mm firing one test panel failed completely along the panel boundary, while the opposite test panel showed partial (incipient) boundary failure in this same region, Figure 5. Testing of the 2.5mm sample panels in the standard test rig produced complete failure for both test panels along the panel boundary, Figure 6. The failure mode observed for these tests was identical to that found in earlier test series [1-5].

Figure 7 shows the FEA simulation of the 3mm panel test rig for a 1000g explosive charge. This FEA simulation and experimental measurements showed similar features to the simulation identified in Figure 3 but with increased overall deformation as well as hinge and 3D corner strain levels.

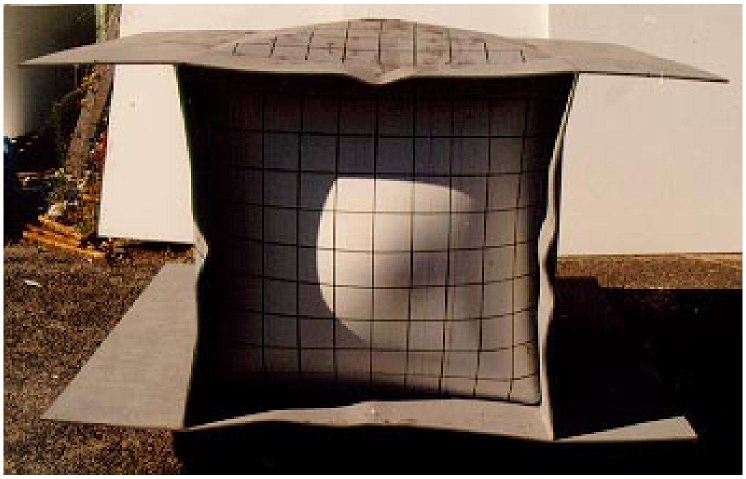

Figure 4. Deformation of 4mm sample panel for 1000g Pentolite charge.

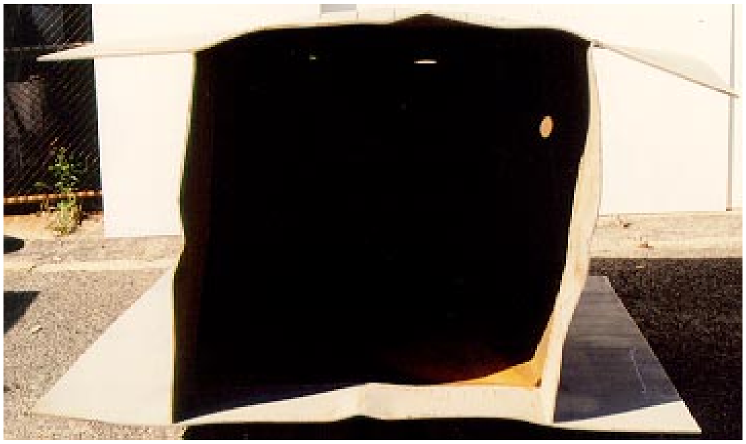

Figure 5. Deformation and failure of 3mm sample panel for 1000g Pentolite Charge.

Figure 6. Deformation and failure of 2.5 mm sample panels for 1000g Pentolite Charge.

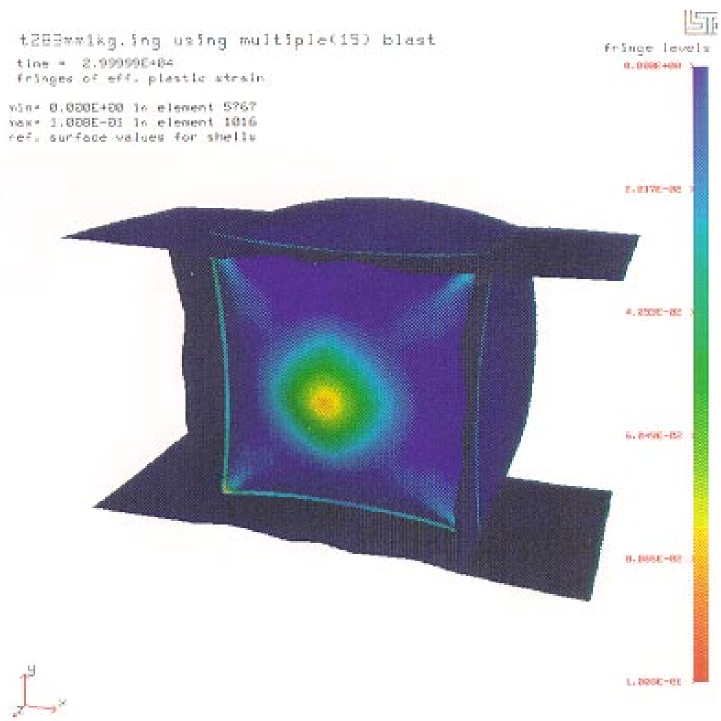

Figure 7. LSDYNA3D simulation of test rig with 3mm test panels for 1 kg Pentolite Charge.

The results of these experimental and FEA simulations as well as previous experiments show that for this type of loading regime, failure occurs at the panel boundaries when the stress/strain levels in the boundary hinge area exceed a yet undetermined critical level. Examination of the failed panel boundary edges showed tensile shear failure surfaces with identical characteristics to those observed in earlier cubicle tests. The proximity of the observed failure position and the FEA predicted high bending strains, previously associated with edge hinge formation, indicates that edge failure may result from a combination of high membrane tensile loading and the severe hinge bending stresses/strains when the panel is below a critical thickness or is weakened by the edge joining procedure or one of its artefacts.

Once failure is initiated in one or more of these high stress/strain hinge or weakened areas, the kinetic energy of the test panels generally continues the failure process through tearing along the panel boundary in the region of the perimeter weld. Although panel boundary failure initially occurs in and adjacent to the hinge/weld attachment region, and may have been initiated by the associated weaknesses introduced by that joining technique, the tearing failure path is not restricted to the weld or the adjacent weld affected zone, but instead follows path of least resistance along the hinge line and which often passes through the parent plate material.

From these FEA predicted and experimental results it can be postulated that panel boundary failure will occur for a given load level when the panel is either below the critical thickness (cross sectional area) or the panel boundary joining technique introduces a weakened region at or adjacent to the panel edge hinge. Accordingly, to resist failure at a given load level, panels must be both of adequate thickness and the edge hinge area must be strengthened by improving panel edge joining quality or by shifting the panel edge join away from the area of intense bending, ie joint attachment redesign. A series of tests has been planned to study the affect of different edge attachment designs based on existing overseas techniques as well as locally developed alternatives.

Unfortunately, the current FEA materials models cannot simulate the failure mode observed for this type of loading regime and accordingly it was not possible to predict the conditions for panel failure. It is hoped that future developments in this area may allow more realistic modelling of panel failure.

Series 3

The third series of experiments was designed to test the reproducability of the test rig and explosive loading conditions. A total of five shots were performed each with 3mm thick test panels and 1000g of Pentolite explosive. Three pressure measurements were made at a panel midpoint as well as 2D and 3D corners.

Although sample panel failure was observed in at least one sample panel from each test, failures were not restricted to the exterior sample edge and occasionally ran partly along the internal frame/sample panel edge join. Examination of these failures indicated poor weld penetration between the frame and sample plate insert which introduced severe weakness in this area. This problem will be addressed in future test rig construction by better quality control and improved sample panel/frame joint design.

Comparisons of pressure measurements for the five tests at the three identified positions generally showed good to excellent reproducability for time of arrival, peak pressure and pressure/time trace features often up to 5msec after explosive detonation. Beyond that time the extreme severity of the pressure loading and resulting dynamic acceleration, deformation and failure response of the test unit, often caused pressure gauge cable failure. However, since all test panel failures were observed to initiate well within the 5msec time these data loses are not considered significant to this study. Figures 8, 9 and 10 illustrate this level of agreement for mid panel, 2D and 3D corner pressure measurements and provide supporting evidence for minimal explosive round to round variation; a minimum requirement for this type of comparative testing procedure. The close correspondence between pressure results for the open vent and sealed vent test rigs for times <5msec indicates that the open vent has an insignificant effect on the occurrence of test panel failure.

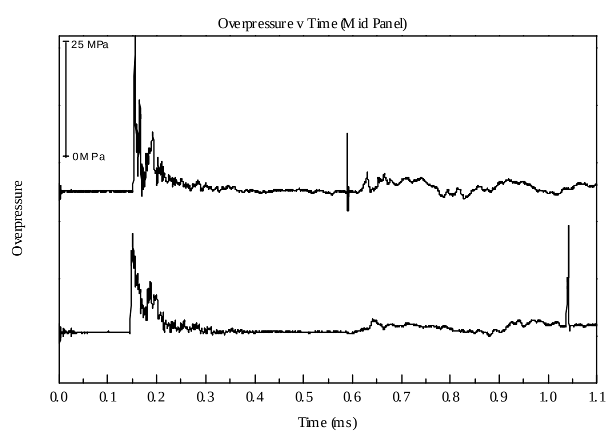

Figure 8. Pressure/time records for 1000g explosive charge at Mid panel position.

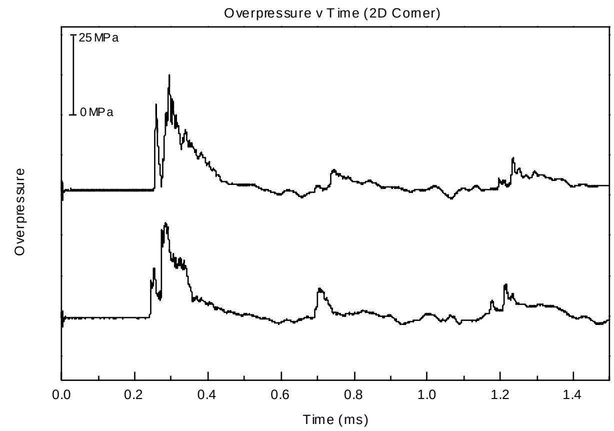

Figure 9. Pressure/time records for 1000g explosive charge at 2D corner position.

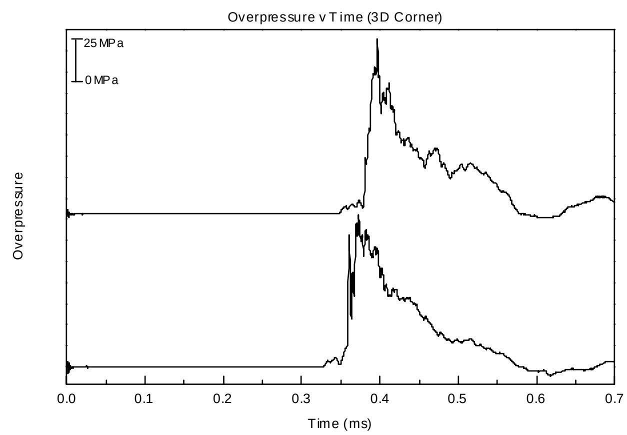

Figure 10. Pressure/time records for 1000g explosive charge at 3D corner position.

4. CONCLUSIONS

The design of an experimental rig for the comparative assessment of the explosive blast loading resistance of steel test panels has been described. Preliminary results from tests using varying explosive charge sizes and panel thicknesses have demonstrated the viability of this test technique in assessing the blast resistance of explosively loaded test panels.

In agreement with previous test results, test panel failure invariably occurred at the panel boundary and is associated with development of a hinge at the panel edge and its associated high strain levels. When coupled with finite element modelling these test results further indicate that the occurrence of test panel boundary failure is, as expected, a function of both panel thickness and the capabilities of the panel boundary attachment characteristics to withstand these high levels of strain developed in the edge hinge area.

Although the FEA modelling was able to demonstrate excellent agreement with the details of test rig plastic deformation, the lack of a suitable materials failure model meant that it was not possible to predict the occurrence of panel failure. With or without failure model refinement the FEA techniques have the potential to provide useful insights into the response of simple engineering structures during dynamic explosive loading. Effort is being applied to develop suitable failure models for this loading regime.

Using the described test design future work aims to examine the efficacy of several alternate edge designs and panel joining techniques which should improve the strength of the panel joint at hinge formation point.

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6. REFERENCES

1. Burman, N.M., Saunders, D.S., Ritzel, D.V., and Buckland, M.E., "Deformation and Fracture of Compartments Subject to Internal Blast Loading", 5th Australian Aeronautical Conference, Australian Institute of Engineers, 13-15 September 1993.

2. Ritzel, D.V., Burman, N.M., Saunders, D.S., and Buckland, M.E., "Internal Blast Damage to Ship Compartments", MABS-13, The Hague, The Netherlands, 13-17 September 1993.

3. Marco, J., Burman, N.M., Buckland, M.E., and Ritzel, D.V., "Modelling the Dynamic Response of a Steel Box Structure to Internal Explosive Blast Loading", Australasian Structural Engineering Conference, 21-23 September 1994.

4. Turner, T.G., Burman, N.M., and Buckland, M.E., "Experimental and Computational Studies of Internal Explosive Blast Damage to Steel Ship Compartments" IEP/ABCA/7 Ninth Quadripartite Conference HMAS Watson, Sydney, Australia, 13-16 May 1996.

5. Walsh, B.E., Burman, N.M., and Buckland, M.E., "SSEP-Manual of Conventional Weapons Data" DSTO-GD-(in publication) 1996.

6. Ritzel, D.V, "Blast Loading in Corners" , The technical Cooperation Programme, TLG3, Defence Research Establishment Suffield, Melbourne, May 1992.

7. LSDYNA3D, Finite Element Analysis Computer Program Suite, Livermore Software Technology Corporation, Jan 1995.

8. Integrated Fluid-Structure Analysis Software, Combustion Dynamics Ltd, Medicine Hat, Alberta, Canada, 1996.