The Use of Hydrocode Modelling in Optimisation of Physical Mitigation Design Solutions for Multiple Weapon Types

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1. Introduction

New large warship designs such as the UK Future Carrier (CVF) require a high degree of survivability to potential enemy attack in war fighting and to terrorist attack during peacetime and peacekeeping operations. Whilst task force and area defence assets will provide protection to major units, operations in the littoral and peacetime port visits offer potential opportunities for attack. The high unit cost of comprehensive ship self defence inevitably drives a compromise solution, whereby full defence may only be available in an alerted task force environment. An increasing risk exists of successful attack at other times.

It follows that hazards to ship's magazines may arise from high speed fragments and blast overpressure near the point of detonation of enemy weapons. Similar hazards may arise from terrorist attack that produces primary or secondary fragment threats to the magazines (e.g. the attack on USS COLE in Aden in 2000).

Figure 1 – Damage to USS Cole at Aden

The explosives risk to the ship and her ship's company when munitions are stowed in a quiescent state in warship magazines is very low. However, the munitions in the magazine may be vulnerable to relatively low energy strike from residual fragments entering the magazines as a result of enemy or terrorist attack. The most vulnerable are those high energy weapons that do not yet meet the Insensitive Munition (IM) goals of STANAG 4439. Some of these are likely to remain in service for many years because of the inevitable pressure on defence budgets.

This paper starts from the premise that one or more fragments may enter a large warship magazine with sufficient energy to initiate a sensitive munition. Two potential needs arise as a result of this premise:

a) In the first place it would reduce the risk if mitigation could be put in place between the fragment and the sensitive munition to prevent or reduce the reaction.

b) In the second place the risk of sympathetic reactions with other weapons could be avoided or reduced if mitigation were to be placed between the sensitive munition and the same or other types of munition in the magazine.

The paper will make proposals for an approach based on experience to specify and execute the necessary assessment and modelling needed to produce solutions to these two requirements. It will also address the requirements for validation of the models used.

2. Background to the Requirements

The stowage arrangements for relatively large quantities of munitions in an Aircraft Carrier, Amphibious Support Ship or Ammunition Supply Ship inevitably result in the need to stow large numbers of weapons in a bulk stowage arrangement. Regardless of whether these munitions are simply stacked and secured to the deck or shock rafts or placed in a mechanised handling system there will be 'stacks' of weapons of the same or different types adjacent to one another.

An energetic fragment that is a potential threat to these munitions may be generated as a result of enemy or terrorist attack or in some circumstances by a failure of high power or high-pressure ship's machinery. Clearly it is possible to provide mitigation or even protection against such fragments by the structure of the ship around the magazine. The type of modelling described in this paper can be used to evaluate and optimise such protection, but that is outside the scope of this paper. It is therefore assumed that the threat fragment succeeds in passing through the boundary structure of the magazine with some residual energy such that it presents a threat to a sensitive munition in the magazine.

There are many In-Service weapons that do not yet meet the IM goals of STANAG 4439. In some cases, despite the best aspirations of National Authorities and Regulators, these will continue in service for many years to come. Even those that do meet the STANAG 4439 requirements may still be vulnerable to a larger mass, high velocity fragment that has greater energy than the assessment/test of IM fragment vulnerability.

In the event that a single munition is initiated as a result of enemy attack or terrorist action, there are three potential results to consider:

a) Firstly the potential for the munition to initiate other munitions of the same type in the same stack.

b) Secondly the potential for the munition to initiate other munitions of the same type in adjacent stacks

c) Thirdly the potential for the munition to initiate other munitions of different types in adjacent stacks.

It follows that if these sympathetic reactions are not contained at this point, further initiation may occur of other munitions in other adjacent stacks leading rapidly to escalation of the event to the point where the loss of the ship is likely.

The first principle to apply to the safety of the design of a magazine is to try to ensure that sensitive munitions are not placed in a position where they may be vulnerable to fragment strike. It is outside the scope of this paper to discuss the many techniques that can be used to limit risk in this way. Suffice it to say that design of the magazine structure and positioning and orientation of munitions and stacks within the magazine will all reduce risk. Attention is therefore required to stowage plans within large ship's magazines to reduce vulnerability. Whilst it may be possible to thereby eliminate the fragment (and blast) threat, for the purposes of this paper, it is assumed that a residual fragment can penetrate to strike a vulnerable munition. It is further assumed that the blast threat from the enemy/terrorist weapon is negligible in comparison with the fragment threat in terms of its ability to initiate a sensitive munition.

3. The Problems to be Solved

The general background above leads to the fact that there is a potential role for physical mitigation barriers between the incoming residual fragment and the 'target' sensitive munition. However, the space available for such mitigation may be limited and the penalty incurred by extra weight, cost and by the inconvenience of having to remove the mitigation to get access to the munitions for use may all be factors in the choice of such mitigation. As a result, it may only be practicable to include a design of mitigation that further reduces the energy of the incoming residual fragment to the point where at least the probability of a high order event is reduced, or at best, the expected result is only burning (Type V reaction). This is one major aspect of assessment and modelling that will be examined in this paper.

PROBLEM 1 – Optimisation of physical mitigation against fragment strike on a munition.

Given that the 'target' sensitive munition may burn or produce a higher order event, the next issue to consider is the effect of this on the stack of munitions (of the same type), which it is secured within. This forms a second modelling or assessment task. In general this will be covered by existing assessment or test results for sympathetic reaction. It may however be necessary to consider these results in the context of a Unit Load configuration or stack of like munitions that may be rather different from the original sympathetic test or assessment scenario.

PROBLEM 2 – Assessment or modelling of sympathetic reaction within a stack of like munitions.

Given that one or more munitions in a given stack has reacted in some way to a fragment strike the next issue to address is the potential effect on adjacent stacks of like or dissimilar munitions. Clearly, this is highly dependent on the scenario in a specific ship or magazine. In this paper an example of this problem will be examined.

PROBLEM 3 – Assessment or modelling of sympathetic reaction between stacks.

Where the results of problem 3 indicate that there are potential hazards of further sympathetic reaction the issue then arises of how to eliminate or reduce this reaction to a tolerable level. Once again, it may be that a different arrangement of stacks within the magazine or orientation or positioning or use of stacks of munitions that are assessed not to react may resolve the issue. Such approaches must be addressed first. If after this, there remains a potential vulnerability then consideration may have to be given to placing physical mitigation between the original ‘target’ stack and the vulnerable stack. This forms the basis of the next modelling requirement.

PROBLEM 4 – Assessment and modelling of physical mitigation between stacks.

For each planned model, it will be necessary to consider how the model can be validated. This will involve two elements. Firstly it is important to conduct a comparison with realistic trial results or practical experience to ensure that gross errors are not present. In other words, is the result at the right or expected order of magnitude? Secondly it may be necessary to conduct specific validation of model parameters for a material or composition that has not previously been validated by previous modelling, tests or trials. It may also be necessary to validate the chosen model itself if it is being required to calculate outside the normal range of activity where confidence already exists. This paper will discuss some approaches to such validations issues.

4. Problem 1

1.1 Model of One Munition Vs a Fragment

In modelling the weapon itself, it will be necessary to take into consideration the fact that the composition to be modelled is contained within a casing. For a fragmentation warhead this will be a thick case, possibly scored or part cut into segments/fragments and probably potted on the outside. For a blast warhead, it is more likely to be a homogeneous, relatively thin case. The outer surface of the warhead case may form part of the missile or weapon outer skin, but it is quite common for the warhead to be ‘sub-calibre’ to the weapon and for there to be a further outer casing forming the external surface of the munition. If this is very thin it may be possible to ignore it for modelling purposes. Otherwise, it should be treated in the same way as the effect of the container described below. The same principles will apply to any other large detonable component of the munition. Where it is a detonable motor that is being considered, it is more probable that the motor casing will form the outer surface of the munition and so this does not present a complication.

The example below shows a single fragment impact on a bare air-to-air missile. The fragment was travelling at a high velocity and easily penetrated the thin outer skin and went on to penetrate the inner casing and impacted the explosive composition. The model calculated the energy transfer during impact to the explosive and the subsequent pressure build up. The pressure build up was sufficient to cause the explosive to detonate. The propagation of the detonation wave can be seen as the red colour in Figure 2 below. In this example the impact of the fragment caused a Type I reaction within the missile therefore some mitigation would be required to prevent this event.

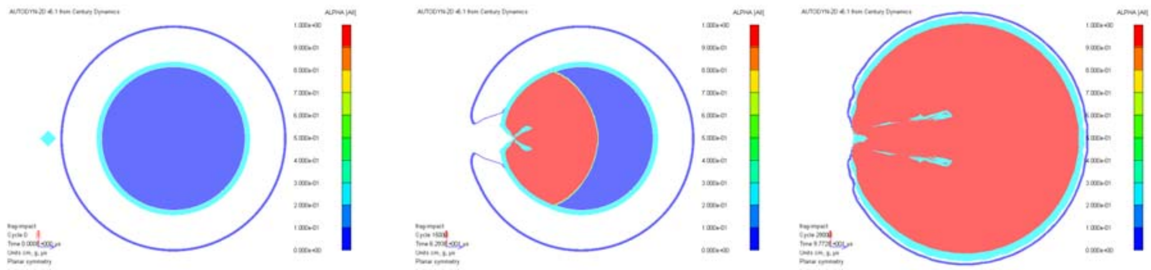

Figure 2 – Fragment impact on missile

1.2 The Effect of the Container.

Where the munition is being modelled in a magazine, it is most likely that it is still in its container. There are therefore two elements of the problem to consider. Firstly, the incoming fragment must do work in breaking through the container before it strikes the munition. This will cause a beneficial reduction in energy of the residual fragment. Once the munition is struck, if it reacts violently, then the container will initially tend to provide further confinement for the explosive reaction and then will be broken apart to form secondary fragments. Both of these effects must be included in the modelling of the system. However, if the container is made of GRP, a detonation reaction will tend to cause the container to be shredded into pieces that do not present a significant hazard to other containerised munitions.

1.3 Modelling the Container

The geometry of the container can be modelled in its true position relative to the missile. When determining whether a fragment will initiate the missile it is only usually required to model the side of the container that is between the fragment and the missile. As the simulation progresses it would then be necessary to model the whole container so that the full effect of the blast confinement and secondary fragmentation can be determined. Figure 3 shows the same setup as described above but with a container in place. The formation of large secondary fragments can clearly be seen.

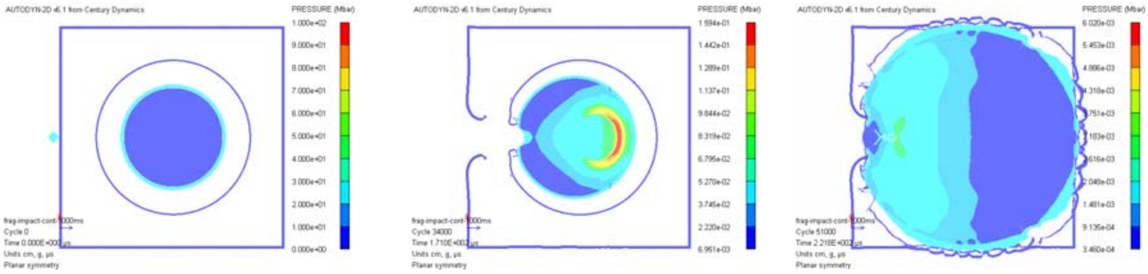

Figure 3 – Fragment impact on a missile in its container

5. Problem 2

This problem can usually be solved by assessment based on known data about sympathetic reaction for the munition. Assuming the stack consists of the same type of munitions in containers, the safety test in accordance with STANAG 4396 is likely to provide data on the response of adjacent munitions of the same nature.

If however, it is desired to model the scenario, this will usually be because the size of the stack is larger and/or more complex than the existing sympathetic reaction trials or assessment data. It may also be necessary to make a model to simulate effects that are not known from the results of the test, such as the mass and velocity of the worst case fragments produced. Where many munitions require to be simulated, the model can take a great deal of time to run.

An example of a sympathetic detonation within a stack of munitions is a stack of three anti tank missiles in their containers. The centre missile was detonated and the red colour shows where the explosive composition has reacted. It can be seen that in this setup both the upper and lower missiles in the stack sympathetically detonate.

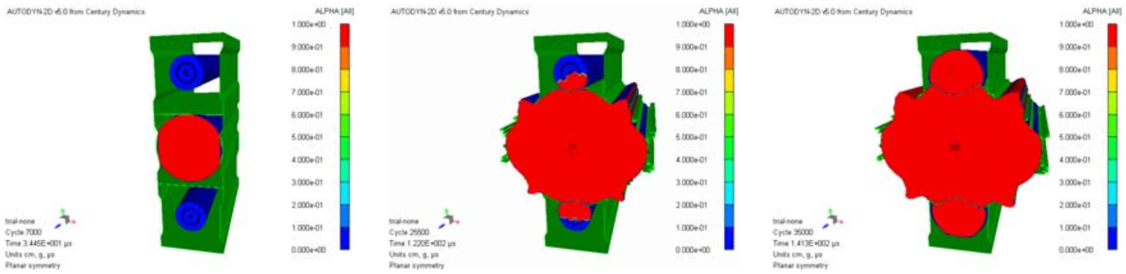

Figure 4 – Sympathetic reaction of missiles within a stack

6. Problem 3

1.4 Like to Like Munition Stacks

The assessment of the likely response of an adjacent stack of munitions will depend on assessment of 3 variables. Given a specific minimum distance apart, the results from Problem 2 will generate a pressure and a ‘worst case’ fragment velocity and mass at that distance from the first munition or stack to react. Comparison with known detonation threshold data (e.g. from the Large Scale Gap Test – see SCC Manual of Tests or STANAG 4488) will indicate whether the compositions in the munition may react to the prompt shock caused by blast overpressure. If not, then the energy of the worst case fragment is examined to determine whether it exceeds any known threshold or reaction data for the munition (e.g. fragment attack or bullet attack tests in accordance with Mil Std 2105B and STANAG 4241). If so, then the type of reaction may also need consideration. For example if the fragment attack response is Deflagration (Type IV), but the composition exhibits Deflagration to Detonation Transition (DDT), then this would probably be regarded as not ALARP or tolerable.

If any of these assessments reveals that a detonation response of the adjacent stack is likely then there is no point in modelling until risk management has been conducted. The aim of the risk management work should be to examine whether the distance between stacks can be increased, or whether a different, less sensitive munition (stack) can be put in this place, or whether a solution involving physical mitigation barriers is required. On the other hand, if there is inadequate data about the likely response then it may be necessary to model the arrangement without mitigation to determine the likely result.

The model used to simulate the stack to stack reaction can be a progression of the setup described in Problem 2. In that case it was found that the first missile detonated would be the primary impactor on an adjacent stack. Figure 5 shows the expansion of the primary blast wave and the impacting fragments on the adjacent stack of missiles. By altering the separation distance the minimum safe separation distance could be determined.

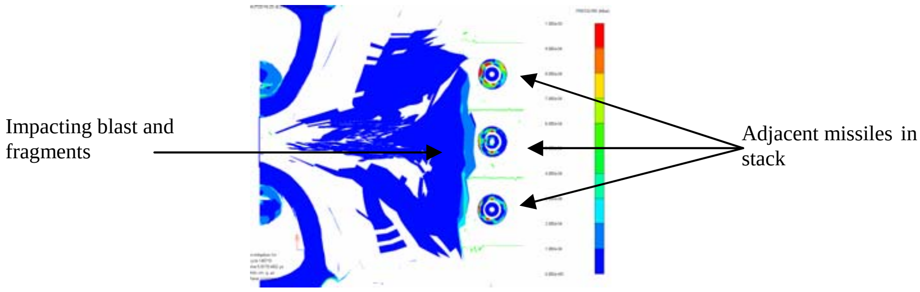

Figure 5 – Adjacent stack reaction

1.5 Stacks of Different Munition Types

The same principles as described above apply to an assessment of dissimilar munitions in stacks. In effect it does not matter what munition nature was the source of the blast or fragments, these threats can be treated in terms of their effect on the next munition stack.

The example shown in Figure 6 is of an anti tank missile, as used previously, detonating next to a large freefall bomb. Despite the close proximity the bomb does not sympathetically react. This is mainly due to the thick steel casing of the bomb absorbing the impacting blast and fragments. Only a low amount of energy is transferred through to the bomb's explosive composition. This shows that the bomb is insensitive to the detonation of the smaller missile and as a result it could be possible to configure the location of the munition stacks so that the bomb stacks were between missile stacks to act as a form of mitigation.

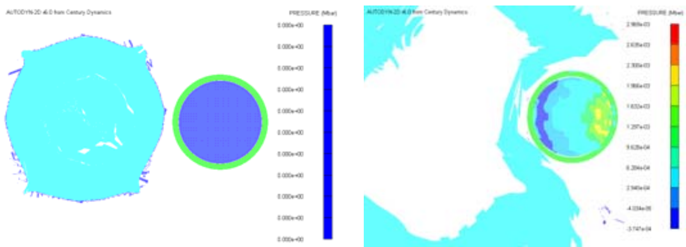

Figure 6 – Anti tank missile detonating next to a large bomb

If a large free-fall bomb was initiated by an event then, due to its high NEQ, it would produce a large overpressure blast wave and many high speed fragments. Figure 7 shows a setup where a large bomb was detonated at a large distance from an air-to air missile. This simulation was run using an Euler solver method so that the blast wave could be accurately calculated over the large distance.

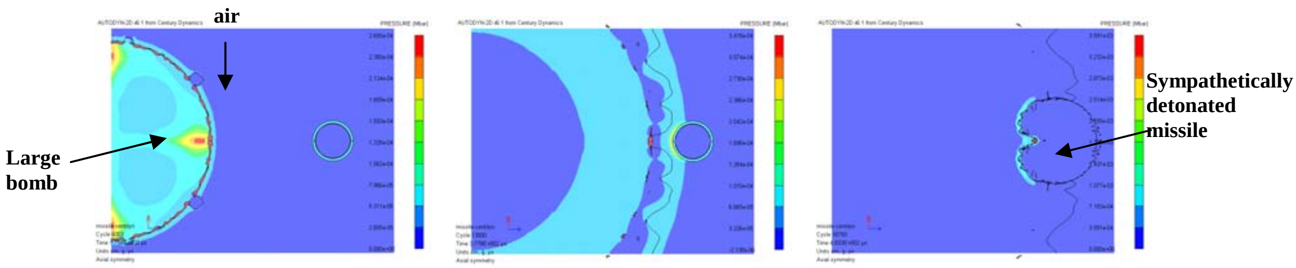

Figure 7 – Large bomb detonating next to an air to air missile

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8. Problem 4

1.6 Provision of Mitigation between Stacks

If the risk management work leads to the conclusion that physical mitigation is required between the stacks, then it must first be established, probably by assessment, what general form this will take. The most cost-effective method may be to place protective mitigation around the most sensitive munition(s) in the magazine. On the other hand, if there are a large number of these it may be necessary to place a less vulnerable munition in the areas of the magazine most vulnerable to attack and then establish what mitigation, if any, is thereafter required to protect other munitions.

Primary considerations in the assessment of mitigation are the simple, practical considerations of space, mass and cost. Clearly an expensive or bulky mitigation material will not be acceptable if it is needed in large quantities. Nor will material of high mass be useful if it thereby exceeds the manual or mechanical handling limitations. The practical issues of how easy it is to remove the mitigation material to get access to the munitions will also be important. These types of considerations will usually result in a reduction of the potential list of materials to a few likely candidates. Finally, there will always be options that relate to whether the mitigation should be placed on the 'donor' stack to reduce the fragment energy and blast emanating from it, or be placed on the 'acceptor' stacks to reduce the effects of the impacting fragments or blast. It is possible to do both in equal or unequal proportions.

1.7 Optimisation of Choice of Mitigation Materials

Given a decision on the considerations above, a short list of potential materials then needs to be further optimised. If possible, this should be done by assessment to reduce cost and computation time. Depending on the model in use, some or all of the materials will exist already within the model. Any that do not exist may have to be assessed by comparison with models of known materials with both better and worse properties to bound the likely response. In the forefront of the choice will be the following materials for the reasons stated in each case:

<u>Water</u>: Water in liquid or gel form is effective at reducing fragment energy. It is also cheap. It will completely stop fragments from the largest HE munitions at a 'thickness' of 1 m. It also has a significant effect in reducing blast energy, particularly in the confined space of a magazine. Furthermore, the container to hold the water will also contribute 2 layers of mitigation (the 'sides' of the container) to the overall mitigation effect. It will obviously be rare to be able to afford a barrier thickness of 1 m in a magazine, so a material with a higher aerial density is more likely to be chosen.

<u>Steel</u>: In a ship, steel in the form of permanent or semi-permanent barriers is cheap if it can be included as part of the build or a major structural change. However, its mass may prevent its use as a barrier for many stacks, or if it has to be removed from the stack for access. If there is potential to divide the magazine into 'bays' or 'bins' to contain groups of munitions using steel boundaries, then this may be a solution to a specific design requirement. Such 'unitisation' of the whole magazine is a good strategy, particularly if the NEQ or Effective NEQ in each bay can be made to be less than the explosive quantity that would cause critical damage or loss of the ship.

<u>Aluminium</u>: Where protection is only required to a part of the munition, perhaps because only the warhead or motor is vulnerable, then aluminium plates may offer a suitable choice. This may be especially true where mass is critical (e.g. where the mitigation plates must be moved by hand to access the store). The advantage of this and other ductile materials is that the effect of multiple fragment strikes and blast will tend to deform the mitigation and to mould it around the munition being protected. However, it does have the disadvantage that aluminium will burn at similar temperatures to those generated by deflagrating or even burning explosive compositions and so may add to the ultimate heat load in the magazine.

Aramid Fibre Materials: Cost becomes a significant consideration in any choice of aramid fibre materials. A typical steel plate will cost 8 to 10 times less than the equivalent mitigation designed using Kevlar. However, the aramid fibre material will be lighter and can be moulded to suit a more complex shape. All types of material in this category will offer good resistance to fragments and will hold together well, even if partially penetrated by many fragments. However, they are vulnerable to high levels of blast, because this causes structural break-up, and will tend to be wrenched from any fixings and projected. Therefore they are best suited to where a small number of munitions require a bespoke shape of mitigation to provide protection at a distance from the 'donor' where blast has decayed somewhat to levels that will not cause immediate physical damage.

Wood/Cellulose Materials: Conversely to aramid fibre materials, products such as plywood, millboard or proprietary composite wood/cellulose boards will tend to break up with the effect of high blast but do not tend to become significant secondary fragments in their own right, unless the whole mitigation material is propelled by the blast wave to impact against the 'acceptor'. They can be treated to improve fire resistance. The key with this type of mitigation is to achieve a sufficient reduction in fragment energy so that the worst case fragment is no longer likely to initiate the protected munition.

When a general choice has been made from the potential materials above, or other materials, it is likely that a small-scale trial will be required to give confidence in the choice. It may also be essential as part of the validation (see below). The aim of such trials is to replicate at least the mid-range fragment conditions, using a sphere fragment for repeatability and direct comparison with the model, applied to a range of thicknesses of the chosen material. The result required is an evaluation of different thicknesses of the material against the same fragment energy. The 'best' solution may then be tested at higher energies that replicate the worst case as a confidence demonstration.

1.8 Modelling the Mitigation

A more effective mitigation material will allow closer spacing of munition stacks and therefore increase the stowage capacity of the magazine. It was described in Problem 2 how the minimum safe separation distance for two stacks of like munitions was found. If mitigation was introduced between the stack then the distance could be significantly reduced. In the example shown in Figure 8 a wood material is placed around each anti tank missile in both stacks. The figure shows the pressure build up and deformation of the missile but no detonation occurred within the explosive composition. It is likely that a Type V reaction may occur but this would probably be acceptable within the magazine. With the introduction of this type of mitigation the minimum separation distance was reduced by 67%, thereby potentially tripling the stowage capacity of the magazine.

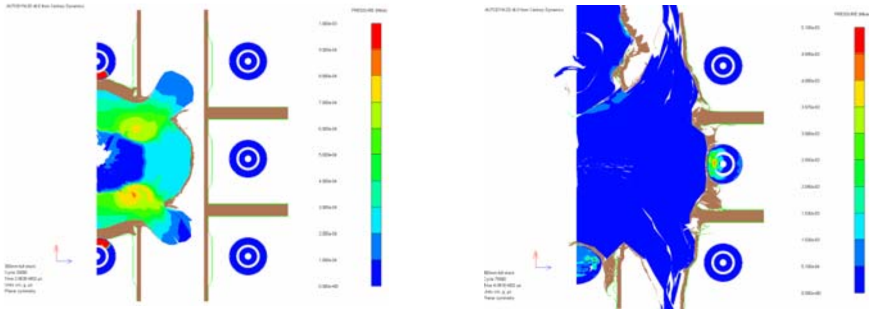

Figure 8 – Mitigated stacks of anti tank missile

9. Validation

1.9 Validation of the Model

The need for specific validation of the model will depend on the past use and confidence in the model parameters for the mitigation chosen and the munitions modelled. If the problem being solved lies within the range of previous work, then it is likely that no validation will be required. Only if the result depends on a new model of a munition or use of a material that has not previously been modelled will validation be essential. A new munition model will need to be validated in terms of both quality control of the modelling process and also by comparison with expected results from proven models. Thus blast energy may be compared with predictions from the many spreadsheets available to ensure that the proper order of magnitude is being achieved. Worst-case fragment energy may usually be calculated by explosives engineering theory as a cross-check.

The results for a mitigation material model will usually be validated by a material parametric trial. As previously discussed, the mid-range result for the model can be directly compared with a practical result using a sphere projected by a suitable gun. Depending on the energy required, this could be by a sabot carrier in a conventional trials barrel or by use of a single stage or 2-stage gas gun of the appropriate calibre. In an extreme case, an explosively projected or formed fragment may have to be used. This could be fired using explosive to project a fragment from a fragmat representative of a warhead casing, or by a true 'explosively formed fragment' designed to replicate the worst-case fragment energy.

10. Summary

In summary, the overall design problem presented by the need to reduce the effects of external and internal threats to a ship's magazine may be broken down into discrete elements for solution. Either assessment or modelling or a mixture of both may solve each element.

The role of assessment is crucial in reducing the many choices down to a short list for the more expensive modelling phase. The assessment may include small-scale practical trials to determine the 'best' options and to give confidence that the correct parametric range of material has been selected to go forward to the model.

Given that the problem to be modelled involves changes of state by explosives reactions, a hydrocode model is the most appropriate solution. Examples are given of the stages to be modelled or assessed to work through a magazine threat problem until a satisfactory design solution is achieved. This can include modelling of the reactions between different munitions.

The model of either the munition or the mitigation may need to be validated to give confidence in the results. The use of spherical 'fragments' is recommended as the best way to achieve repeatability between validation trials and different models.