SHOCK RESILIENCE OF STRUCTURAL PILLARS IN NAVAL VESSELS

(DOI No: 10.3940/rina.ijme.2017.a1.385)

J C Rigby, **C Moss**, BMT Defence Services LTD, UK, and **G Thomas,** University College London, UK

SUMMARY

Although structural pillars are extensively used in commercial vessels, traditionally their use on board UK warships has been discouraged. This is due to the tendency of pillars to "punch through" the deck when subjected to the high impulse loading of shock from underwater explosions (UNDEX). There are however many spaces within naval ships that would significantly benefit from the wide-open spaces created from the use of pillars as opposed to full bulkheads, such as machinery rooms, mooring decks and accommodation flats. This paper re-addresses the question of a shock capable pillar, looking at how a pillar can be designed or mounted to increase its resilience to shock from underwater explosions. It is proposed that the advice against the use of pillars in warships could be unfounded; this is supported by the fact that not all navies reject their use. The results of this study imply that as long as the pillar is sited properly on primary structural members, then pillar buckling should occur long before "punch though".

NOMENCLATURE

ε	Strain
$\dot{\varepsilon}$	Strain Rate (s^{-1})
θ	Decay Constant (s)
ν	Poisson's Ratio
σ_{yd}	Dynamic Yield Stress (N m^{-2})
σ_{yh}	Hardening Yield Stress (N m^{-2})
A	Initial Yield Stress (N m^{-2})
A1/A2	Constants
B	Hardening Constant
D	Strain Rate Constant
E	Young's Modulus (N m^{-2})
K1,K2	Constants
n	Hardening Exponent
P	Pressure (N m^{-2})
P_{Max}	Peak Pressure (N m^{-2})
q	Strain Rate Constant
R	Stand Off Distance (m)
t	Time (s)
t_0	Time of Shockwave Arrival (s)
W	Charge Weight (kg)

1. INTRODUCTION

1.1 BACKGROUND

Although structural pillars are extensively used in commercial vessels, traditionally their use on board UK warships has been discouraged. This is due to the perceived tendency of pillars to "punch through" the deck, when subjected to the high impulse loading of shock from underwater explosions (UNDEX). This occurs when the pressure and rapid acceleration from the shockwave forces the pillar to penetrate through the supported deck or down through the bottom of the ship.

There are however many spaces within naval ships that would significantly benefit from the clear open spaces created from the use of pillars as opposed to full bulkheads (Eyres, 2007), such as machinery rooms, mooring decks and accommodation flats.

1.2 PREVIOUS WORK

A large amount of the fundamental work on shock from underwater explosions was conducted immediately after the Second World War, sparked by the loss of ships by attack from German U-Boats. This research included experimental shock trials as described by Brown (1987) and analytical considerations such as the work of Cole (1948). Cole is still highly cited and stands as the basis for many modern shock pressure prediction techniques. The papers of the mathematician Sir Geoffrey Taylor (1963) are another well-cited source, presenting analytical equations for shock loaded plate velocity from theoretical considerations.

The development of computational simulation tools such as Finite Element Analysis (FEA) has opened up a new area of research for the structural response of structures to shock loading. While it is widely accepted that due to validation problems these simulations could never replace experimental shock testing, it is argued they can be used to provide initial estimates of structural response and to supplement and interpolate between experimental test data (Mair *et al*., 2003).

Ramajeyathilagam *et al*. (2000) developed a simplified model of an unstiffened plate and used experimental data to successfully validate their FEA model. Rajendran and Lee (2009) used analytical methods to calculate the behaviour of blast loaded plates and provided a detailed critique of current UNDEX FEA techniques. They concluded that both numerical and analytical methods provide good correlation with experimental models (Rajendran *et al*., 2007; Rajendran and Narashimhan, 2001).

Using experimental data from Ramajeyathilagam *et al*. (2000), Jen and Tai (2010) validated an FEA model of a stiffened plate grillage. They used a fluid-structure interaction code to solve the problem and looked at the grillage section in isolation from the rest of the hull in order to simplify the calculations. Rajendran (2009) and Veldman *et al*. (2006) both used Cole's equations of similitude to calculate the loading pressures on a flat plate due to UNDEX shockwaves.

This allowed a "dry" assessment model to be created without the need for fluid-structure interaction codes. Both papers show good correlation with experimental results (Rajendran, 2009; Veldman *et al*., 2006) demonstrating that valid conclusions can be made without the expensive fluid-structure interaction codes, as long as the assessment does not last more than the UNDEX time period when predictions from Cole's equations alone begin to break down.

Bradbeer (2013) investigated changes in structural design configurations over the last 20 years and their effect on shock performance. Bradbeer describes the evolution from the complex structures of the Cold War compared to the cost-driven warships of the modern era. A comparison was made using a range of FEA models with different structural styles under the same shock loading. The study concludes that the application of simplified low cost styles leads to significantly elevated shock response motions, especially with the application of asymmetrical stiffeners with larger spacing.

To summarise there has been a significant amount of work previously completed on shock from underwater explosions, especially using full-scale shock trials. Unfortunately due to the classified nature of the subject the majority of this experimental data is unavailable. It has not been possible to source a publically available reference for pillar design specifically under shock loading, highlighting a potential gap in the literature. Of the classification societies considered only GL (2012) and Lloyd's Register (2014) specifically mention shock loading, and only Lloyd's Register recommend against the use of pillars "below the waterline" (DNV, 2012, GL, 2012 and Lloyd's Register, 2014).

1.3 RESEARCH QUESTION

The primary research question behind this study was "*How can a pillar be designed or mounted to increase its resilience to shock from underwater explosions*?"

2. METHODOLOGY

2.1 OVERVIEW

There were many different ways in which to approach the primary research question. Possible methods included full-scale experiments, scaled model experiments and numerical techniques. Experimental analysis, either full sized or scaled, would have placed a restriction on the number of models that could be assessed due to time/cost considerations. A numerical analysis using FEA however enables a large range of concepts to be assessed. Therefore a numerical analysis using FEA was deemed to be the most appropriate methodology, enabling a large range of concepts to be assessed within the cost and time limits available.

In order to prevent the need for an expensive and computationally demanding fluid-structure interaction analysis, a "dry" FEA model was utilised. This is when the resultant underwater shock pressure is applied directly to the hull without modelling the propagation of the shockwave through the water. This method has previously been implemented by Rajendran (2009) and Veldman *et al*. (2006), with noted success. A method to assess the comparative performance of different pillar arrangements was also required, looking at both the shock loads and the "everyday" loading scenario. The criteria of assessment for both load cases was deck displacement. In the shock scenario the criteria evaluated the deflection transferred to the upper decks, while in the static load condition it measured

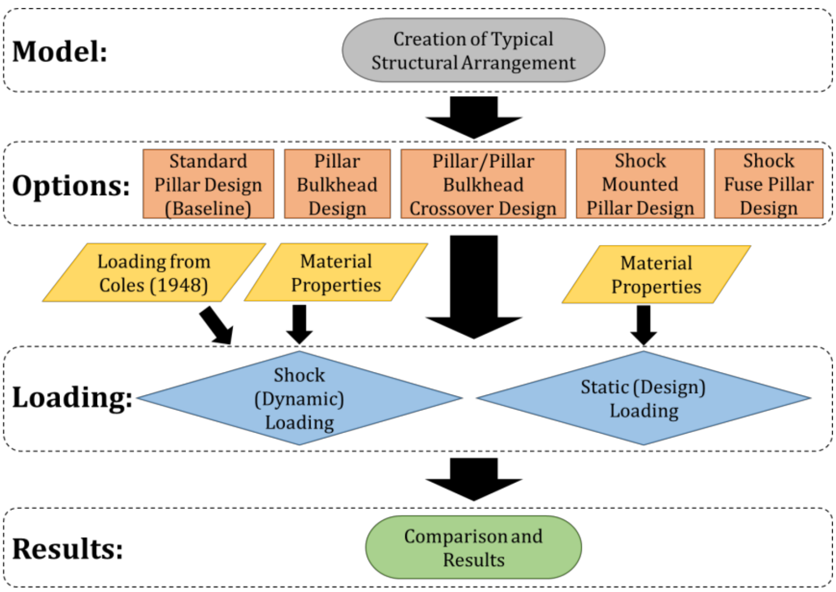


Figure 1 – Research methodology overview flow chart

the support provided by the pillar. An overview of the project methodology is presented in Figure 1.

2.2 SECTION TYPES

When looking at shock capable pillars, the design concepts were broadly split into two categories (as shown in Figure 2), those with solid structure and those with spring/damper arrangements.

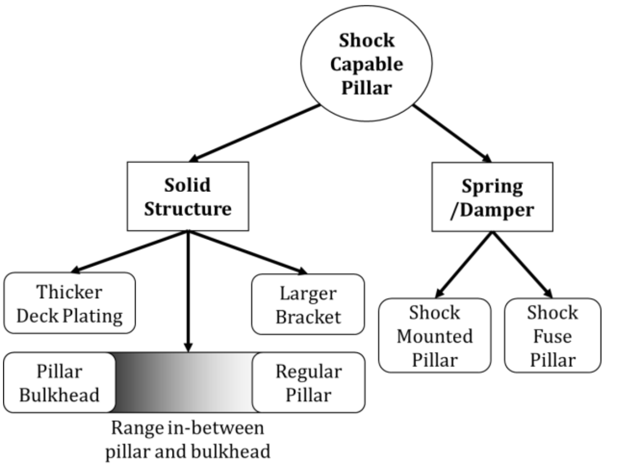


Figure 2 - Alternative pillar section types

The solid structure solutions mainly involved creating a range between the full bulkhead (known to have high shock performance) and the regular pillar as well as increasing the size of supporting brackets and doubler plates. Spring/damper based solutions involved adding a shock mount or a plastically deforming shock fuse into the system to absorb the energy or release the energy over a longer period of time.

2.3 REPRESENTATIVE SHIP STRUCTURE

The representative ship structure used in the project was primarily taken from the NATO Frigate Replacement for the 1990s (NFR-90) (Schaffer and Kloehn, 1991) design, with an increased frame spacing as proposed by Bradbeer (2013) to reflect modern building practices. The NFR-90 design was chosen, as it is an unclassified reference and a typical example of post-Cold War warship design.

Instead of modelling an entire ship or hull section, only the key aspects of the ship to this study were assessed. Figure 3 presents the extents of the model with only the double bottom and the deck above the pillar in the model (Double deck height). The structure represents half of a ship section between bulkheads, idealised with a flat bottom. This simplified section allowed for the quick production of multiple models and provided comparisons between the different structural arrangements.

2.4 LOADING AND BOUNDARY CONDITIONS

The dynamic model was loaded with an underwater shockwave pressure calculated using Cole's (1948) equations of similitude. The load produced by the explosion can be approximated by an almost instantaneous peak in pressure, followed by an exponential decay, as presented in Figure 4. This shape is replicated by Cole's equations as presented in Equations 1 to 3.

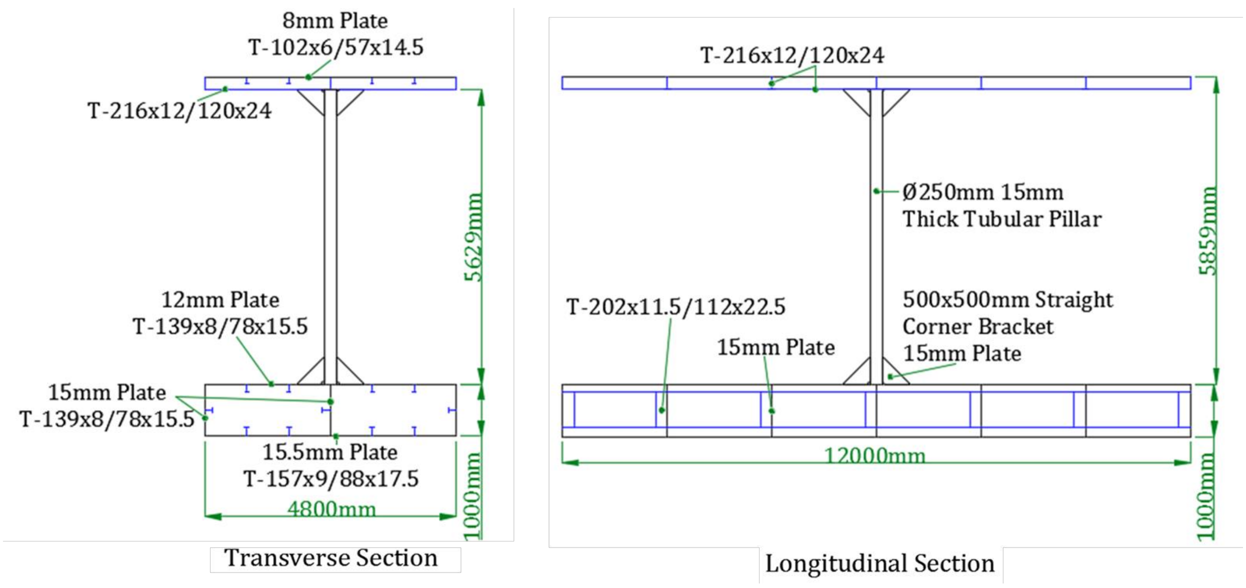


Figure 3 – Modelled structure dimensions

$$P_{Max} = K1 \text{ x} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A1} \quad \text{(eq1)}$$

$$\theta = K2 \text{ x} W^{\frac{1}{3}} \text{ x} \left(\frac{W^{\frac{1}{3}}}{R} \right)^{A2} \quad \text{(eq2)}$$

$$P = P_{Max} \text{ x} e^{(t-t_0)/\theta} \quad \text{(eq3)}$$

Where P_{Max} is peak pressure, W is charge weight, R is stand-off distance, θ is the decay constant, P is pressure in relation to time, t is time, t_0 is time of shockwave arrival and A1, A2, K1, K2 are constants.

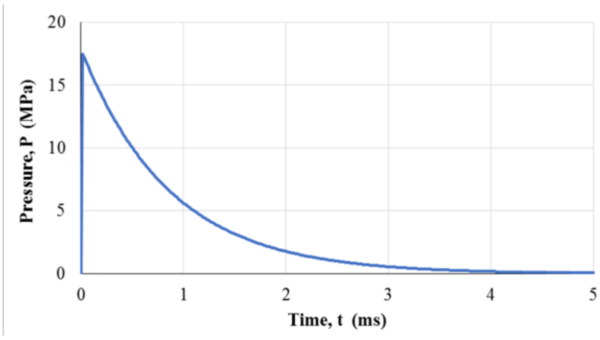


Figure 4 - Typical underwater shock pressure-time curve created using Cole's (1948) equations of similitude

The boundary conditions of the model were applied as depicted in Figure 5. The double bottom structure was constrained around the edges of 3 Deck and the hull plating from displacement in the X and Y directions. This prevented the decks from peeling inwards while still allowing the double bottom to move upward in the Z direction. The edge of 2 Deck was fully constrained in order to prevent rigid body motion and simulate the constraints of the surrounding structure.

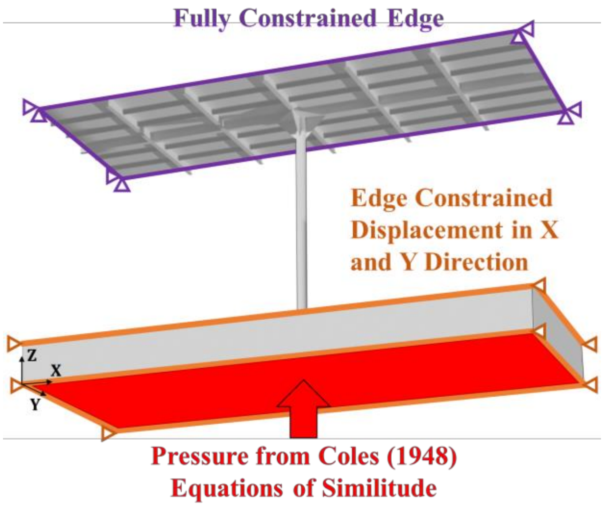


Figure 5 – Model Boundary Conditions

It is understood that this arrangement of structure and boundary conditions does not directly simulate the exact ship structure and response. Instead it provides a conservative analogous representation allowing comparison between different pillar arrangements.

2.5 ELEMENT DETAILS

Pressure from underwater shock is a time dependant loading condition requiring a dynamic transient solution. The available non-linear dynamic solvers for the FEA models can be split into two main groups, explicit and implicit solvers. Explicit solvers calculate each time step as a function of the previous time steps, assuming a linear change in displacement between them (Crisfield, 1991). This explicit solver requires small time steps to produce a stable solution. Implicit solvers in contrast calculate each time step as a function of both previous and current time step values, assuming a constant average acceleration between time steps (Crisfield, 1991). This implicit model requires the matrix to be inverted and convergence checks preformed for each time step, requiring greater computational effort.

In general, explicit codes are preferred for high velocity impact problems (Hale, 2013) and implicit codes are preferred for applications driven by low frequency responses (Crisfield, 1991). Due to the short time period and high-energy accelerations, explicit solvers are recommended for underwater shockwave loading assessments (Bradbeer, 2013); similarly due to the longer loading periods implicit codes are recommended for gas bubble loading. As this study only considered the initial shock loading, an explicit solver was selected; using Ansys Workbench for the model, the AUTODYN (Ansys, 2015) solver was selected.

For the analysis SHELL 163 elements were used (Ansys, 2015), these are four-noded linear shell elements used for explicit codes. Two-dimensional shell elements were used throughout the model design as a better representation of the flat sheet steel panels, in comparison to three-dimensional hexahedron elements (Hale, 2013). The SHELL 163 element selected is a linear element as only linear explicit elements were available for use within the Ansys software. It is understood that linear elements are normally undesirable due to their poor performance in bending (Cook, 2001), however due to the high strain nature of explicit problems, a close mesh is normally required enabling linear elements to provide a suitable solution.

2.6 MATERIAL PROPERTIES

Finding the right material properties is a critical part of producing an accurate FEA solution. Throughout the project the following materials were used:

- **Mild steel** – selected for the main model construction and some validation cases;

- **High Strength Steel** – used for some validation cases;
- **Rubber** – used as part of a "PD" Type shock mount.

When conducting a non-linear analysis it is vital to allow for the strain-rate dependency of the deflection (Liu *et al*., 2015) as well as material hardening (Paik, 2007). In this work the Cowper-Symonds relation (Cowper and Symonds, 1957) was selected to model the non-linear relationship of the material, as summarised in Equation 4 (Cowper and Symonds, 1957). The Cowper-Symonds relationship was chosen due to its applicability to shell elements, with data available for the behaviour of steels (Ramajeyathilagam *et al*., 2000).

$$\frac{\sigma_{yd}}{\sigma_{yh}} = 1 + \left(\frac{\dot{\varepsilon}}{D}\right)^{\frac{1}{q}} \qquad \text{(eq4)}$$

Where σ_{yd} is dynamic yield stress, σ_{yh} is yield stress accounting for hardening, $\dot{\varepsilon}$ is strain rate and D and q are strain rate constants.

The use of shell elements meant that complex material failure models such as Johnson-Cook (Ozturk, 2010; Banerjee *et al*., 2015) were not applicable. Instead the simpler method of applying a failure strain was used, which is a method proven to be effective for high strain simulations by Guimaraes *et al*., (2014). If an element is found to have met the failure criteria then the element is "eroded" (Ansys, 2013), essentially deleting the element but retaining the attached momentum.

The material properties for steel used in the project are presented in Table 1.

Table 1 - Material properties for steel, values taken from Ramajeyathilagam *et al*. (2000) and Guimaraes *et al*. (2014)

Material Property	Mild Steel	High Strength Steel
Density, ρ	7800kg/m^3	7800kg/m^3
Young's modulus, E	210GPa	210GPa
Poisson's ratio, ν	0.3	0.3
Initial yield stress A	250MPa	400MPa
Hardening constant, B	600MPa	600MPa
Hardening exponent, n	0.21	0.21
Strain rate constant, D	80	80
Strain rate constant, q	4	4
Failure strain, ε	0.8	0.8

Natural Rubber is a hyperelastic material and therefore experimental data is required in order to determine the material properties (MSC Software, 2010). The type of rubber available for use was limited by the accessible data. Axel Products, Inc. (2015) kindly provided strain data for a typical filled natural rubber test sample under a series of different load cases. There are a large number of different hyperelastic relationships available (Wadham-Gagnon *et al*., 2006), however the simpler Neo-Hookean formulation was chosen due to limited experimental data.

3. MODEL DETAILS

A large range of different pillar arrangements were then created and tested against the same shock loading. The eight main pillar designs assessed are outlined in Figure 6 and described as follows:-

(a) + (b) Regular/Baseline Pillar Design

The circular pillar configuration is the most popular due to the high buckling strength of a cylinder (Okumoto et al., 2009). The pillar is designed to Lloyd's Naval Ship Rules (Lloyd's Register, 2014) and includes small brackets and a doubler plate at the top.

(c) Large Bracket

The large bracket model was created to determine the effect of brackets on the pillar strength. Brackets are commonly used to shorten the "effective span" of the pillar, reducing the chance of buckling and reducing stress concentrations at the joint. The brackets also spread the load over a larger section of deck, which could prevent "punch through".

(d) Full Pillar Bulkhead

A pillar bulkhead is a vertically stiffened minor bulkhead employed in place of a pillar as recommended by Lloyd's Naval Ship Rules (Lloyd's Register, 2014) for use below the waterline. The structural configuration of the pillar bulkhead was designed to Lloyd's Naval Ship Rules (Lloyd's Register, 2014) and checked against buckling using Chalmers (1993). The bulkhead runs the full length of the compartment (12 metres).

(e) Half Bulkhead

A range of models was also created between the pillar and the pillar bulkhead designs, in order to determine if there was a performance crossover where the best aspects of a pillar and a bulkhead are combined. First a half bulkhead model was created with half the length of the full bulkhead but the same scantlings.

(f) Third Bulkhead

A third compartment length model was also created using the same scantlings as the full bulkhead model.

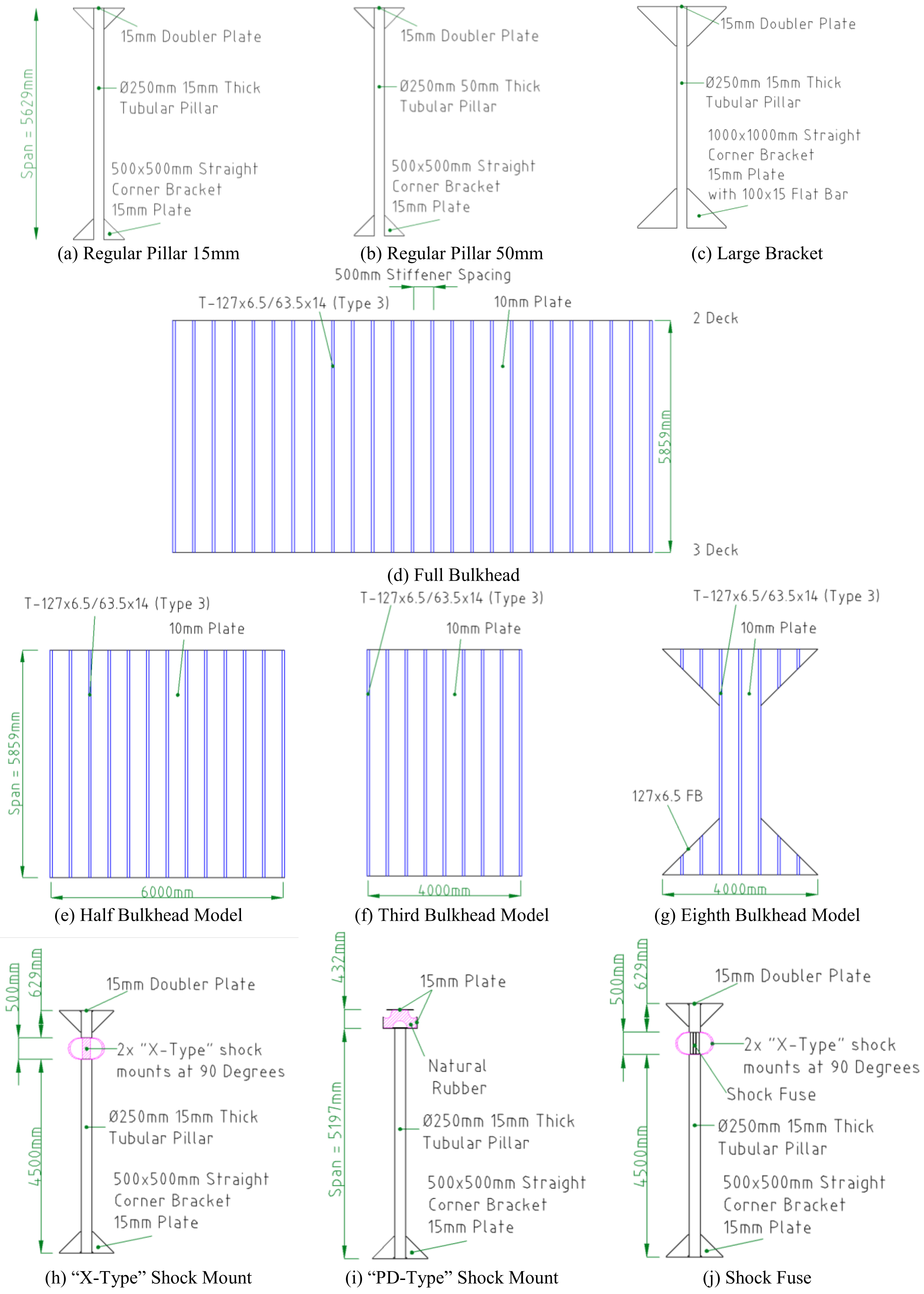


Figure 6 - Model details and dimensions (Not to Scale)

(g) Eighth Bulkhead

The "Eighth Bulkhead" structure, is a hybrid structure between a bulkhead and a pillar. The structure was designed to meet Lloyd's Naval Ship Rules (Lloyd's Register, 2014) requirements for cross sectional area and plate thickness as well as having large brackets to transmit load to the adjacent web frames.

(h) + (i) Shock Mount

Shock mounting is a commonly used practice to protect equipment and machinery on board a ship from shock accelerations. The principle behind the mount is to store the input energy in the mounting and release it slowly, thus reducing the acceleration and peak loads (Hutchinson, 2015). Usually the shock mount is used to secure equipment to a deck with the only forces generated due to the weight of the equipment (NAVSEA, 1995). In the case of a pillar, the loading scenario is different, as not only will the mount be required to take the static support load, but the mount is crushed between the pillar and the adjacent deck during shock loading. It is noted that the addition of the shock mount at one end of the pillar turns the usual Fixed-Fixed connection into a Fixed-Pinned connection. Using Eulers buckling formula this Fixed–Pinned connection would be predicted to have a lower buckling strength (Chalmers, 1993). It is however expected that the energy absorbed by the mount would reduce the pillar loading and overcome the effect of the Fixed-Pinned connection.

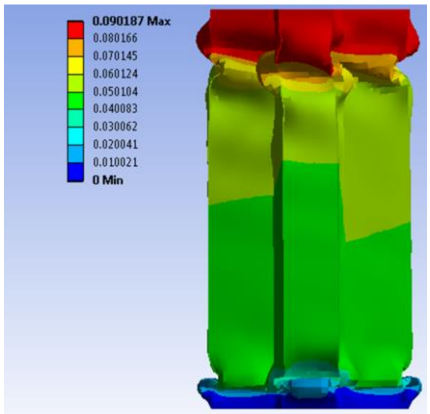
Existing shock mounts designs were investigated, assessing their ability to scale up the force/weight range and the ability of the mount to maintain alignment. The two designs selected as having the greatest potential were the "X-Type" mount and the "PD-Type" mount (Caparo, 2015).

The "X-Type" mount is a combination of leaf springs with a damping compound in-between. The "X-Type" mount was positioned at the top of the pillar with two mounts at 90 degrees to form a cross shape. The mount was modelled using a series of linear spring damper elements. The "PD-Type" mount is essentially a large section of shaped rubber used to absorb energy like a spring; rubber material was specified for the model instead of using spring elements. The mount model used the manufacturers proportions (Caparo, 2015) at four times the size to allow for greater deformation under load.

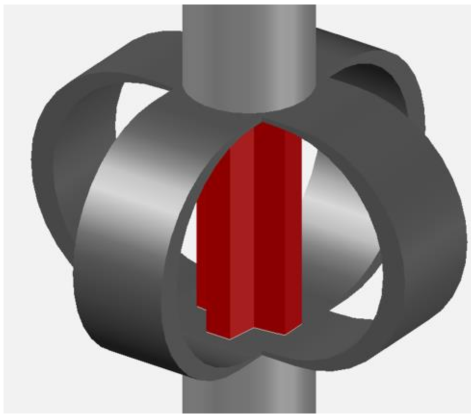
(j) Shock Fuse

A shock fuse is a small section of a pillar that is designed to plastically deform or buckle absorbing the shock load like a crumple zone in a car (Reddy *et al*., 2015). The shock fuse section has been designed to produce stable progressive collapse (Figure7a) as tested by Reddy *et al*. (2015), using a multiple corner prismatic shape to absorb more energy (Tang *et al*., 2012). To maintain alignment and provide deck support after the shock loading, two "X-Type" shock mounts were employed. A close up view of the proposed shock fuse design is presented in Figure 7c, the section highlighted in red is the shock fuse. The fuse is designed to be a disposable part that can be replaced after use and at sea.

(a) Experimental testing of progressive stable collapse in pillars reproduced from Reddy *et al*. (2015)



(b) Numerical analysis of shock fuse buckling



(c) Shock Fuse design

Figure 7 – Shock Fuse

4. VERIFICATION AND VALIDATION

Verification of the simplified structural model was taken from previous numerical work completed by Bradbeer (2013) and Zong *et al*. (2013). This has shown that when a hull is subjected to a shock load from underneath, the double bottom structure will deform first, pushing the bottom inwards. This phenomena is only present during the initial reaction to the shock load before the whole hull is forced upwards. The assumptions made in the boundary conditions and load cases are therefore valid for the initial time period (0 – 25ms) and for a limited double bottom deflection. Mesh verification checks were also completed ensuring element shape quality and by preforming a mesh sensitivity analysis.

Validation of the model was provided using experimental data of a shock loading scenario. Due to the limited availability of experimental data from shock trials, the validation model was limited to a flat plate subjected to underwater explosions as conducted by Ramajeyathilagam *et al*. (2000). This is a simplification of the structure compared to the complex grillages of a ship, however it still validates the loading conditions developed from Cole's equations (1948) and the FEA approach.

The experiment performed by Ramajeyathilagam *et al*. (2000) tested a 4mm thick, 0.3m by 0.25m rectangular flat steel plate against a range of explosives and stand-off distances. The plate was bolted around its edges, therefore a fixed boundary condition in all degrees of freedom was implemented.

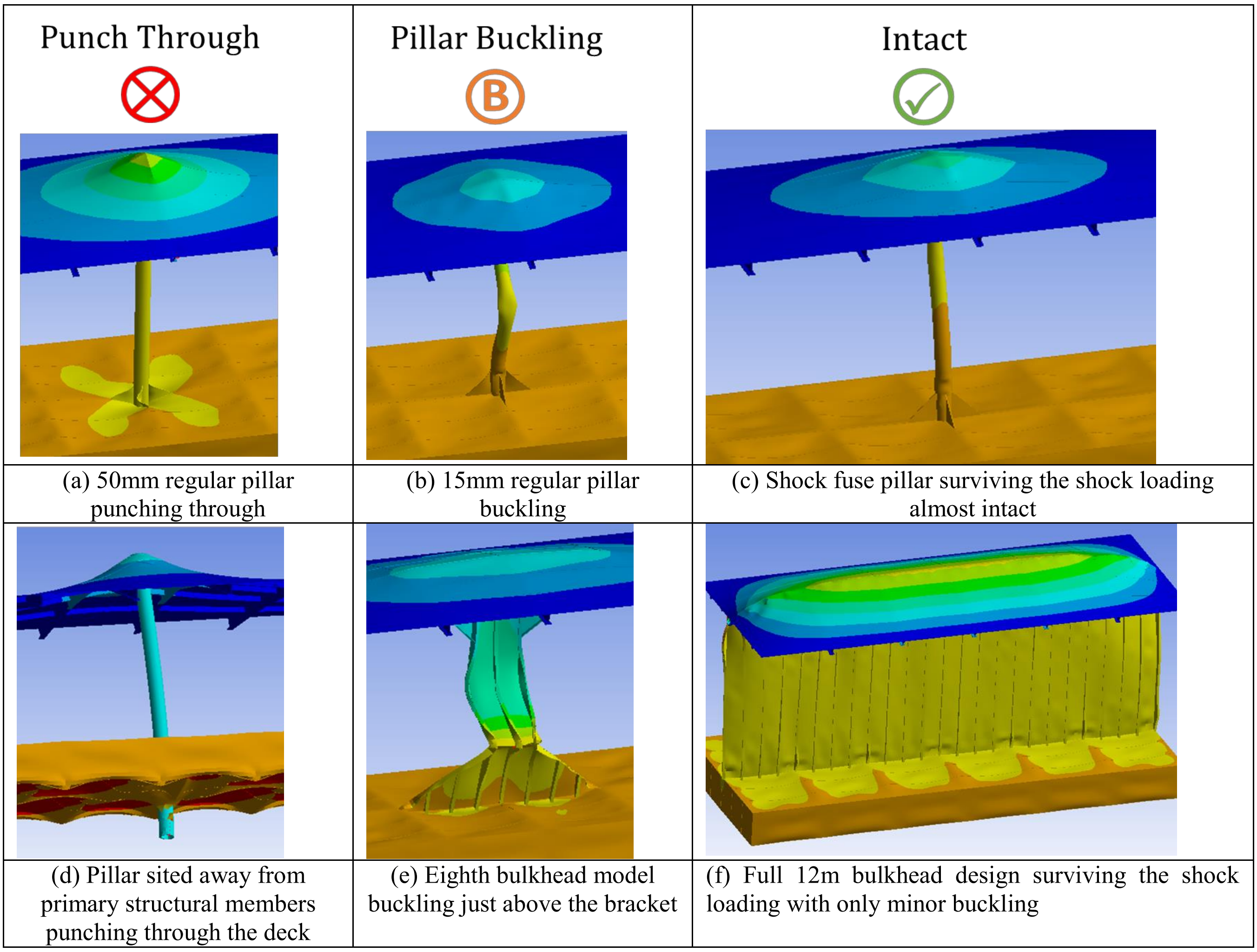
The permanent deflection values determined from the FE analysis showed good agreement with the experimental data measured by Ramajeyathilagam *et al*. (2000). With a maximum percentage difference of 5.7% the results were well within allowable limits, thus validating the loading condition, supporting equations and FEA approach.

5. RESULTS AND DISSCUSSION

In all of the models created the overall performance of the structure can be summarised into three groups:

- Punch Through – Penetrates the deck above/below;
- Buckling – Structure buckles under loading;
- Intact – Both pillar and decks are structurally intact.

Figure 8 provides a key to the different symbols used to represent these groups as well as presenting the characteristic behaviour.



(a) 50mm regular pillar punching through

(b) 15mm regular pillar buckling

(c) Shock fuse pillar surviving the shock loading almost intact

(d) Pillar sited away from primary structural members punching through the deck

(e) Eighth bulkhead model buckling just above the bracket

(f) Full 12m bulkhead design surviving the shock loading with only minor buckling

Figure 8. Examples of pillar behaviour to loading of shock factor 1.0

5.1 REGULAR PILLAR

The graph in Figure 9 presents the 2 Deck displacement for two 250mm diameter circular pillars with plate thicknesses of 15mm and 50mm for varying shock factors. It can be seen that the regular 15mm pillar buckled at an imperial shock factor of 0.63 despite being designed for a static load comparable to an imperial shock factor of 1.0. This is partially believed to be caused by the computational discretisation of the structure. As the pillar was constructed from a number of flat shell elements the cylindrical shape was replaced by a hexagonal outline with a reduced buckling strength. The buckling is not predicted by the strain based failure criterion but is highly dependent on the pillar cross section and geometry. A quick validation of the buckling failure result can be taken from a comparison against previous experimental tests of buckling pillars (Mohanraj *et al*., 2011). The predicted overall failure pattern agrees with experimental data with the pillar buckling at mid-point due to the high slenderness ratio. To model the behaviour of the pillar without buckling the pillar plate thickness was increased to 50mm and showed punch through to occur at a shock factor of around 0.9. A shock factor of 1.0 was taken as the highest test load as above this value hull plate failure is likely to occur (Ramajeyathilagam *et al*., 2000).

The total deflections of the two different pillar thickness arrangements are presented in Figure 8a and 8b. The punch through behaviour of the 50mm thick pillar can be seen in Figure 8a, with strong lines visible where the FEA solver has removed the connection between the two elements due to material failure. This shows that the material would begin to crack and rupture under the given load/defection. It can be concluded that without unrealistically large pillar scantlings and high shock pressures, complete pillar “punch through” is extremely unlikely if the pillar is located on primary structural members.

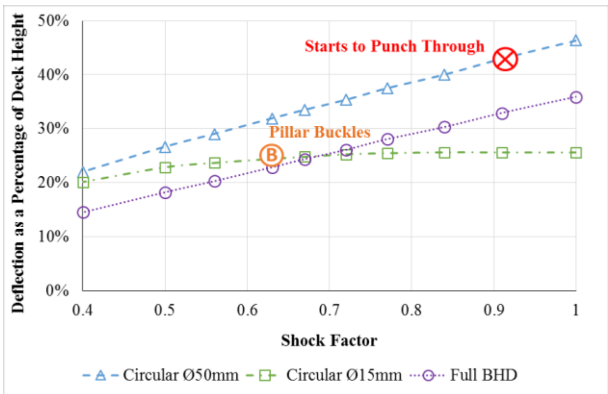


Figure 9 - 2 Deck deflection of different circular pillar thicknesses for varying shock factors

The pillar design was located on a web frame between a double bottom bulkhead and a large longitudinal girder. This heavy structure prevented the pillar from breaking through the deck but does however cause failure at hard points where the stiffeners connect with the side shell and major bulkheads. This is believed to be the much more common source of failure from pillars under shock loads.

An additional study was completed considering the consequences of seating a pillar away from the primary structure, so it is only supported by plate. As expected subjecting this arrangement to the same shock factor of 1.0 caused the pillar to easily punch through the bottom of the structure, as shown in Figure 8d. This behaviour highlights the importance of seating the pillar on primary structural members and double bottom bulkheads. It therefore appears that this pillar design will only punch through if either incorrectly seated or if the section is massively overdesigned.

5.2 LARGE BRACKET PILLAR

Next an assessment was completed to evaluate the effectiveness of using bracket support structures and doubler plates in combination with a pillar. From the graphs in Figure 10a it can be seen that large brackets reduced the 2 Deck displacement. The bracket structure distributed the shock force over a larger area reducing deflection, as well as creating a better support for static loads.

5.3 PILLAR BULKHEAD

The 2 Deck displacement performance of a full length pillar bulkhead is presented in Figure 9, alongside circular 15mm and 50mm diameter pillars. As originally hypothesised, the full bulkhead had superior performance with a lower deflection rate without buckling, while also preventing punch through. This outlines the full bulkhead design as the target to meet/approach compared to the poor performance of the regular pillar. Total deflection results presented in Figure 8f show only minor buckling at the corners of the bulkhead.

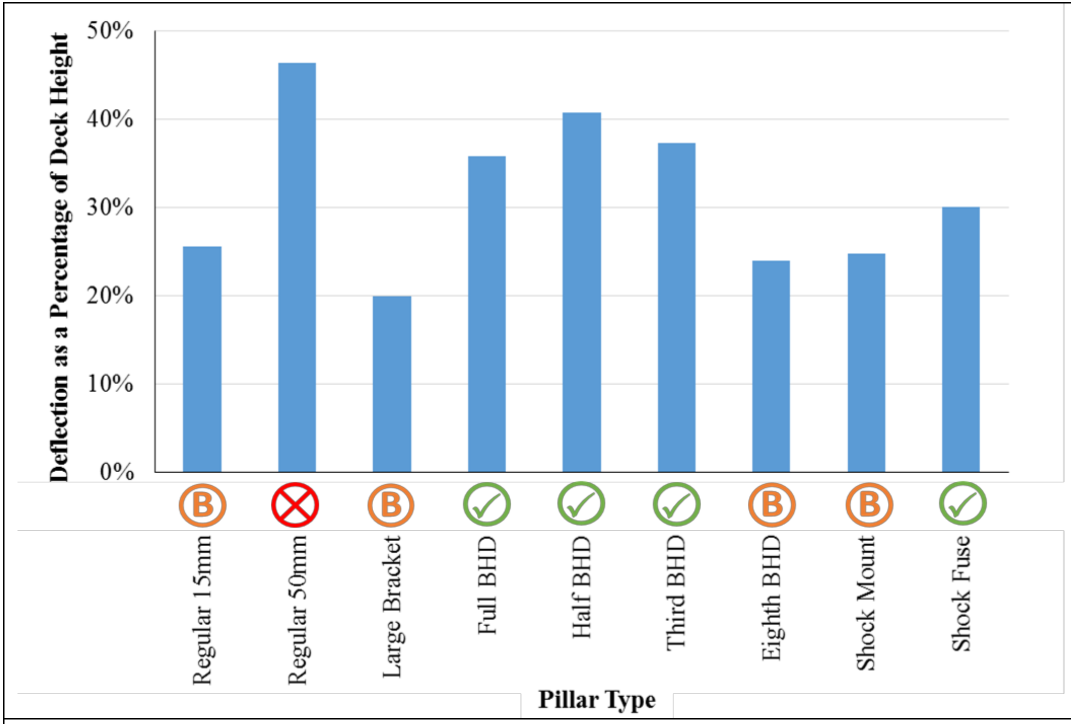
5.4 RANGE BETWEEN PILLAR AND PILLAR BULKHEAD

The comparison of the range between full pillar bulkhead and pillar models in Figure 10a shows that, as expected, the full bulkhead offered the best performance. It is interesting to note the slight peak in the 2 Deck displacement for the half bulkhead. This was due to the alignment of the half bulkhead; as the ends of the bulkhead were not located on a web frame, the edges deflected further upwards. The original eighth bulkhead design did not survive the shock load, buckling just above the bracket (Figure 8e) and producing only a very small 2 Deck deflection.

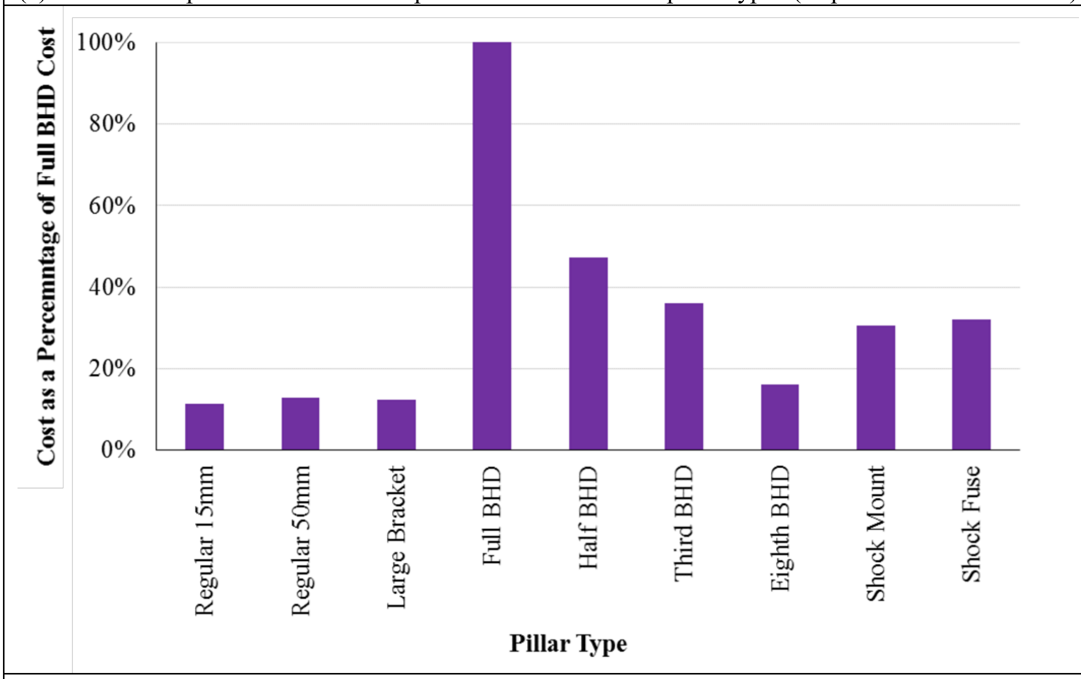
The most efficient bulkhead design was the third bulkhead model, having the smallest amount of structure without buckling. However with a length spanning two web frames it is still a pillar bulkhead instead of a pillar substitute and was therefore discounted as a valid option.

5.5 SHOCK MOUNTED PILLAR

A range of different shock mounts were modelled with different stiffness values, however similar deflection values were seen by all. Increasing the stiffness of the mount slightly increased the 2 Deck deflection and reduced the overall deflection. Although all of the regular 15mm thick pillars tested with the shock mounts buckled, either by bottoming out the spring/shock mount or from the force transferred by the spring.



(a) Overall comparison of 2 Deck displacement for different pillar types (Imperial shock factor 1.0)



(b) Comparative cost estimations for different arrangements

Figure 10 – Overall pillar comparison

Additional models were then created with a thicker pillar plating to prevent buckling. The results showed a large increase in 2 Deck displacement resulting in "punch through". From this it can be determined that a shock mount alone cannot realistically be used to protect the pillar from "punch through" at high shock loads. The high forces will either cause the mount to bottom out (if low stiffness) or push through the deck (if high stiffness).

Additional tests were however completed at a lower shock factor of 0.5, with positive results. Both "X-Type" and "PD-Type" mounts were found to successfully counter the shock load and prevent the pillar from buckling.

5.6 SHOCK FUSE

The results for the shock fuse in Figure 10a show that there was a small increase in 2 Deck deflection compared to regular and shock mounted models, however this design also prevented buckling, even with the 15mm pillar arrangement, due to the shock fuse absorbing the energy. After the shock loading the fuse was distorted and deformed but the shock mounts around the fuse provided temporary deck support against the static load; these shock mounts would provide a suitable supporting structure until the fuse is replaced by the crew. Overall the shock fuse design should be considered a success, preventing punch through and pillar buckling.

Whilst the presented shock fuse model, using spring elements, cannot model the deformation behaviour exactly, this model can still be used as an indicator of the feasibility of the shock fuse idea. The results of this analysis suggest that the principle could work if the component could be constructed.

5.7 OVERALL COMPARRISON

In summary, a comparison of performance for the key designs is shown in Figure 10a. Only the bulkhead configurations and the shock fuse designs survived the 1.0 shock factor loading without buckling or punching through. The regular 15mm, eighth bulkhead and shock mount models had similar displacement values and all buckled, saving the deck above from significant damage. The results suggest that pillar "punch through" is unlikely to be a problem and will only occur if the pillar is incorrectly seated or the pillar section is overdesigned.

If the pillar structure is not required to maintain structural integrity after the shock loading then the large bracket and eighth bulkhead models stand out as a good solution with satisfactory performance in both static and dynamic assessments. If however the pillar is still required to support the load above, then the shock fuse offers the only non-bulkhead style solution.

An estimate of the comparative costs of the different pillar arrangements is presented in Figure 10b. Allowance was made for weld complexity by costing the bulkhead arrangements for robotic welding and the pillar arrangements for manual welding. Despite these allowances, the full bulkhead arrangement stands out as being the most expensive, requiring more material and welding. The cheapest arrangement is given by the standard pillar design. The shock fuse design however strikes a good balance between construction cost and performance, producing a cost-effective shock capable design.

It is noted that in some cases additional partitioning or wall panels may be required to use a pillar in the place of a full bulkhead. No cost additions for partitioning were considered for this study, but they may be relevant for the use of pillars in accommodation flats.

6. CONCLUSIONS

In conclusion the main implication of this work is that the advice against the use of pillars in warships due to "punch through" could be unfounded. The results imply that as long as the pillar is sited properly on primary structural members, then pillar buckling should occur long before "punch though"; although care should be taken to prevent failure at surrounding deck hard points. It is noted that for some applications pillar buckling below the required shock factor would be also be unacceptable. In this case where the item is required to maintain structural integrity, either a shock fuse pillar arrangement or a pillar bulkhead section is recommended. Equally it is suggested that regular pillars sited away from the bottom structure would experience a lower shock loading and could be justified for use by suitable structural calculations.

From the results it can also be concluded that both brackets and doubler plates should be employed to produce a pillar with increased shock capability. Full bulkhead arrangements were found to provide the best shock performance with a third compartment length bulkhead required to prevent buckling.

The results suggest that shock mounts would need to be excessively large to be used on their own to survive high shock loading, this would in turn lead to poor static performance. The use of shock mounts in conjunction with shock fuses could however be a successful combination providing a cost-effective solution that can successfully survive a high shock factor.

There are however a number of limitations to the study which will affect the accuracy of the results. First of all the modelled section only accounted for a small part of the hull, this conservatively ignored the effect of the side hull strength and simulates pressure loading on the entire bottom structure. Additionally to simplify the analysis the model was assumed to be in deep water on a single hull type with no internal fluids. Finally the assessment only took into account the initial shock wave, as this is the loading period most likely to cause internal shock damage (Keil, 1961); the following bubble pulse loading could however cause additional damage to the already weakened structure.

A few items are highlighted for future research. The next step of the research should look at creating a full ship/compartment FEA model, to create a more realistic picture of the structural reaction to shock. Additional research and experimental testing is also required to fully validate the numerical simulations and obtain full material properties for the rubber used in shock mounts. One of the key limitations of the current model is the simplicity of the material failure prediction, this failure criterion could be improved either by using different FEA software or an external program. Finally more research and experimental shock testing should be conducted on the shock fuse to optimise the design and consider the practical aspects of construction/fitting.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the help of many colleagues at UCL and BMT Defence Services Ltd who supported the project. Acknowledgement is also given to the work conducted by Ramajeyathilagam *et al*. (2000), providing experimental data for model validation and to the work by Reddy *et al*. (2015) into progressive stable collapse and for the reproduction of Figure 7a.

8. REFERENCES

1. ANSYS 2013. *ANSYS Mechanical Users Guide*. Canonsburg: Ansys.
2. ANSYS 2015. Ansys Element Library [Online] Available at: http://www.ansys.stuba.sk/html/elem_55/chapter3/ES3-1.htm [Accessed: 27 July 2015].
3. Axel Products, Inc. 2015. *Natural Rubber Experimental Data* [Online] Available at: http://axelproducts.com/ [Accessed: 15 August 2015].
4. BANERJEE, A., DHAR, S., ACHARYYA, S., DATTA, D. and NAYAK, N. 2015. *Determination of Johnson cook material and failure model constants and numerical modelling of Charpy impact test of armour steel*. Materials Science and Engineering*: A* 640, pp. 200–209.
5. BRADBEER, N.I.C. 2013. *Implications for Underwater Shock Response of Adopting Simplified Structural Styles in Warships*. UCL.
6. BROWN, D.K. 1987. *Post War Trials: Test Against Destroyers*. Warship XI(41), pp. 28–34.
7. CAPARO. 2015. *Solutions in Vibration, Shock and Noise Control* [Online] Available at: http://www.caparo-dynamics.com/ [Accessed: 1 July 2015].
8. CHALMERS, D.W. 1993. *Design of ships' structures*. London: HMSO.
9. COLE, R.H. 1948. *Underwater Explosions*. Princeton: Princeton University Press.
10. COOK, R.D. ed. 2001. *Concepts and applications of finite element analysis*. 4th ed. New York, NY: Wiley.
11. COWPER, G.R. and SYMONDS, P.S. 1957. *Strain-hardening and strain-rate effects in the impact loading of cantilever beams*. DTIC Document.
12. CRISFIELD, M.A. 1991. *Non-linear finite element analysis of solids and structures*. Chichester ; New York: Wiley.
13. DNV. 2012. *Rules for Classification of High Speed, Light Craft and Naval Surface Craft*.
14. EYRES, D.J. 2007. *Ship construction*. 6th ed. Amsterdam ; Boston, MA: Butterworth-Heinemann.
15. GL. 2012. *GL Rules for Classification and Construction Naval Ship Technology*. . Available at: http://www.gl-group.com/infoServices/rules/pdfs/gl_iii-1-1_e.pdf.
16. GUIMARAES, G.P., DOS SANTOS, J.L., DE SOUSA LIMA, E. and DE VASCONCELOS CARDOSO, A.L. 2014. *DOP Ballistic Investigations with Explicit Analyses*. In: Sao Paulo, Brasil: ESSS.
17. HALE, S. 2013. *Getting Started With ANSYS Workbench Explicit Dynamics*. CAE Associates.
18. HUTCHINSON. 2015. *Shock Mounts* [Online] Available at: http://www.stopchoc.co.uk/products_shock_mounts.asp [Accessed: 11 July 2015].
19. JEN, C.Y. and TAI, Y.S. 2010. *Deformation behaviour of a stiffened panel subjected to underwater shock loading using the non-linear finite element method*. Materials & Design 31(1), pp. 325–335.
20. KEIL, A.H. 1961. *The response of ships to underwater explosions*. DTIC Document.
21. LIU, Y., DONG, D., WANG, L., CHU, X., WANG, P. and JIN, M. 2015. *Strain rate dependent deformation and failure behaviour of laser welded DP780 steel joint under dynamic tensile loading*. Materials Science and Engineering: A 627, pp. 296–305.
22. Lloyd's Register. 2014. *Rules and Regulations for the Classification of Naval Ships, January 2014*. London: Lloyd's Register
23. MAIR, H.U., REESE, R.M. and HARTSOUGH, K. 2003. *Simulated ship shock tests/trials*. In: LFTE Simulation.
24. MOHANRAJ, E.K., KANDASAMY, S., MALATHY, R. 2011. *Behaviour of steel tubular stub and slender columns filled with concrete using recycled aggregates*. Journal of the South African Institution of Civil Engineering 53(2).
25. MSC Software. 2010. *Nonlinear Finite Element Analysis of Elastomers*.

26. NAVSEA. 1995. *Shock Design Criteria for Surface Ships*. Portsmouth, NJ.
27. OKUMOTO, Y., TAKEDA, Y., MANO, M. and OKADA, T. eds. 2009. *Design of Ship Hull Structures*. Berlin, Heidelberg: Springer Berlin Heidelberg.
28. OZTURK, G. 2010. *Numerical and Experimental Investigation of Perforation of Steel Plates by Oblique Impact*. Ankara: Middle East Technical University.
29. PAIK, J.K. 2007. *Practical techniques for finite element modelling to simulate structural crashworthiness in ship collisions and grounding (Part I: Theory)*. Ships and Offshore Structures 2(1), pp. 69–80.
30. RAJENDRAN, R., PAIK, J.K. and LEE, J.M. 2007. *Of underwater explosion experiments on plane plates*. Experimental Techniques 31(1), pp. 18–24.
31. RAJENDRAN, R. 2009. *Numerical simulation of response of plane plates subjected to uniform primary shock loading of non-contact underwater explosion*. Materials & Design 30(4), pp. 1000–1007.
32. RAJENDRAN, R. and LEE, J.M. 2009. *Blast loaded plates*. Marine Structures 22(2), pp. 99–127.
33. RAJENDRAN, R. and NARASHIMHAN, K. 2001. *Performance evaluation of HSLA steel subjected to underwater explosion*. Journal of Materials Engineering and Performance 10(1), pp. 66–74.
34. RAMAJEYATHILAGAM, K., VENDHAN, C.P. and RAO, V.B. 2000. *Non-linear transient dynamic response of rectangular plates under shock loading*. International Journal of Impact Engineering 24(10), pp. 999–1015.
35. REDDY, S., ABBASI, M. and FARD, M. 2015. *Multi-cornered thin-walled sheet metal members for enhanced crashworthiness and occupant protection*. Thin-Walled Structures 94, pp. 56–66.
36. SCHAFFER, R.L. and KLOEHN, H.G. 1991. *Design of the NFR-90*. Naval Engineers Journal 103(2), pp. 29–49.
37. TANG, Z., LIU, S. and ZHANG, Z. 2012. *Energy absorption properties of non-convex multi-corner thin-walled columns*. Thin-Walled Structures 51, pp. 112–120.
38. TAYLOR, G.I. 1963. *The Scientific Papers of Sir Geoffrey Ingram Taylor : vol. 3 Aerodynamics and the mechanics of projectiles and explosions*. Cambridge: Cambridge University Press.
39. VELDMAN, R.L., ARI-GUR, J., CLUM, C., DEYOUNG, A. and FOLKERT, J. 2006. *Effects of pre-pressurization on blast response of clamped aluminum plates*. International Journal of Impact Engineering 32(10), pp. 1678–1695.
40. WADHAM-GAGNON, M., HUBERT, P., SEMLER, C., PAIDOUSSIS, M.P., VEZINA, M. and LAVOIE, D. 2006. *Hyperelastic modelling of rubber in commercial finite element software (ANSYS^{TM})*. In: Proceedings of Conference on SAMPE 2006.
41. ZONG, Z. ZHAO, Y. and LI, H. 2013. *A numerical study of whole ship structural damage resulting from close-in underwater explosion shock*. Marine Structures 31, pp. 24–43.