Small Combatant Accidental Damage Extents

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Abstract: A cost benefit analysis has been conducted to understand how the extent of transverse watertight subdivision as a result of accidental damage extent requirements drives vessel cost, and where the balance lies between cost of increasing survivability and cost of vessel loss. The results of this investigation suggest that a 15% accidental damage extent is appropriate for a small naval combatant.

A great deal of work has been conducted in recent years concerning the derivation of appropriate accidental damage extents for naval vessels; this work has focussed predominantly on extents determined as a percentage of vessel length. Traditionally however, small vessels less than 90 metres in length have struggled to comply with such a standard and have consequentially been certificated against an extent based on number of compartments.

This paper explores the impact on small combatant design of moving from a two compartment damage requirement to a 15% length damage extent through a series of design explorations on four current small combatants. The implication of a 15% extent is examined with regard to the respective changes in ship size and watertight definition required to achieve compliance, and corresponding conclusions are presented.

Key words: Damaged Stability, Accidental Damage Extents, Damage Templates, Longitudinal Damage Extent, Damaged Stability Standards

1. Introduction

An ongoing package of work is being undertaken by the UK MOD Naval Authority to assess the suitability and applicability of current naval damage extents, split into accidental and hostile categories. As part of this work a method for conducting a cost benefit analysis to determine accidental longitudinal damage extents has been developed [1][2][3]. This work had previously focused on longitudinal accidental damage extents for vessels above 92m waterline length and uses factors such as vessel value, cost of transverse subdivision and estimates of annual probability of an accident.

Under current UK MOD stability standards [5], vessels below 92 metres waterline length are not required to comply with a percentile accidental longitudinal damage extent; instead a damage extent is defined with regards to number of compartments, where a compartment is considered to be a minimum of 6 metres in length. Current UK MOD longitudinal accidental damage extents are seen as:

Vessels of length less than 30 metres:
- *Any single main compartment*

Vessels of waterline length between 30 metres and 92 metres:
- *Any two adjacent main compartments, a main compartment is to have a minimum length of 6 metres*

The design and cost impact of moving from such a standard to a standard defined by percentage of waterline length was previously unclear. It was not known if a percentage damage extent, output from the cost benefit analysis, would be prohibitively expensive to comply with, or lead to an increase in the size of small combatants in order to achieve compliance.

As the next phase of the derivation of accidental longitudinal damage extents the following work has been conducted and is presented herein:

- A sensitivity study to understand the sensitivity of the cost benefit approach to key inputs.
- An assessment of a suitable longitudinal extent for a vessel under 92 metres.
- A study to assess the design implications of a damage extent defined by percentage of waterline length on four in-service small naval combatants.

Cost Benefit Analysis Sensitivity Study

2.1 Cost Benefit Approach

A study was conducted, to assess whether the upfront cost of increased subdivision, and hence survivability is a worthwhile investment to reduce the risk of losing a vessel to accidental damage. This increased subdivision is linked to the design longitudinal damage extent such that the best value for money design standard can be applied. Figure 1 shows a typical example of the cost-benefit curves produced, and shows a point of inflection where the additional cost of designing to a higher standard does not represent worthy investment. This point of inflection is therefore the optimum damage extent to which a ship should be designed.

As the cost benefit approach is based on ship specific cost assumptions, it is an unsuitable method for the development of a generic standard; instead the method is suited to the development of standards for specific classes or individual ships. The cost benefit study undertaken by the UK MOD looked at three different classes of vessels: a destroyer, a high capability frigate, and a small combatant. A full explanation of the approach with underpinning assumptions is laid out in [1].

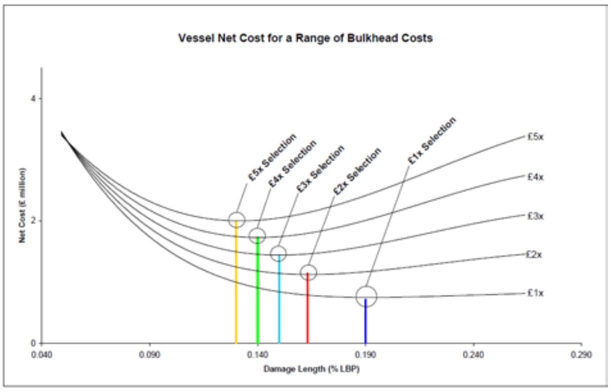

Fig. 1 - Example of a vessel net cost for a range of bulkhead costs

2.2 Sensitivity Study

There are several key assumptions upon which the cost benefit analysis is dependent; there were further scrutinized in order to provide assurance that the model is robust. These three areas are:

- Likelihood of loss
- Cost of additional bulkheads
- Unit Procurement Cost (UPC)

2.2.1 Likelihood of loss

The likelihood of vessel loss is a function of the probability of the vessel experiencing an accident multiplied by the probability of the damage length being exceeded. This was derived from merchant vessel collision statistics which are discussed in detail in [1]. The applicability of using merchant data to derive naval standards is outlined in [3] where the conclusion states that using merchant vessel accidental damage is credible due to the accident rates being found to be similar. As the sample size for Naval vessels is small, the calculated accident rate varies greatly with each individual incident; as a result, it is appropriate to assess the impact that this variance has on the overall calculated optimum design damage length. The baseline value used is derived from the average of the mercantile sources available which is an accident rate of 1.6 x 10^{-02} per annum. The upper bound was 1.5 times the baseline level, and the lower limit half the baseline level with the RN average accident rate used by way of comparison.

2.2.2 Cost of additional bulkheads

In order to determine the cost of introducing additional bulkheads into an established design a design study was conducted. The starting point for the study was that the design of the vessel had been developed and that the drawing work was complete. Uncertainty in bulkhead cost estimates arise from more indeterminate factors such as the potential complexity of rearranging a general arrangement and re-routing ship systems around a new bulkhead. For a small combatant, the baseline cost per bulkhead was assumed as £130k however it was significantly increased to £500k when input into the sensitivity study in order to encompass all unaccounted costs.

2.2.3 Unit Procurement Cost

A large spread (±25%) was assumed from the baseline values as the confidence in an assumed cost of procuring a new ship is low. It is likely to be cheaper to procure ships produced as part of a class than a one-off replacement vessel built after all sister vessels have been constructed. For a small combatant, £25m was considered the baseline value.

2.3 Sensitivity Results

Varying the parameters outlined above, each of the net cost benefit curves were produced and the optimum design damage extents were tabulated into look up tables with an example shown in Table 1.

Table 1 - Sensitivity table of varying UPC and likelihood of loss

		Likelihood of Loss			
	Relative	0.5 x Baseline	RN Statistics	Baseline (UK Vessel Damage Baseline)	1.5 x Baseline
UPC	-25%	17.30%	17.70%	17.80%	18.20%
	-10%	17.40%	17.80%	18.00%	18.50%
	-5%	17.40%	17.90%	18.10%	18.50%
	Baseline	17.50%	18.00%	18.10%	18.60%
	5%	17.50%	18.00%	18.20%	18.70%
	10%	17.60%	18.10%	18.20%	18.70%
	25%	17.70%	18.20%	18.40%	18.90%

The output of the study is shown in Table 2. It can be seen that within the bounds of the variation in the sensitivity analysis, the design damage extent is always greater than the current DEF STAN 02-900 15% damage extent standard.

Table - 2 Output of sensitivity study

Vessel	Baseline cost	Optimum cost-benefit damage extent	Range
Destroyer	£1b	22.7%	19.9%-26.1%
Frigate	£500m	21.0%	18.4%-25.2%
Small Combatant	£25m	18.1%	16.5%-24.9%

One conclusion drawn from the data above is that with the upfront cost of building warships, it is prudent to design the vessel to be more survivable due to the relatively small cost of increased survivability through subdivision at the design stage even when assuming the worst case bulkhead cost.

The sample size for the RN accident rate was considerably smaller than the merchant vessel statistics and showed that there was a reduced accident rate meaning individual incidents have a much larger effect on the calculated accident rate. As the optimum design points for all classes were found to be above the current DEFSTAN 02-900 requirements, the next step of the study was to consider what annual accident rate would result in a standard of 15% representing the optimum solution from a cost-benefit perspective. Table 3 shows the output of this work and shows that for smaller vessels the annual probability of vessel loss would need to be an order of magnitude less than mercantile statistics, and for larger, more expensive vessels two orders of magnitude.

Table - 3 Likelihood of loss required for 15% damage extent to be optimum

	Optimum cost-benefit damage extent	Likelihood required for 15% damage extent
DD	22.7%	$\approx 2.1 \times 10^{-4}$
FF	21.0%	$\approx 3.8 \times 10^{-4}$
OPV	18.1%	$\approx 2.0 \times 10^{-3}$
	Baseline accident probability	1.6×10^{-2}

The analysis was all carried out theoretically and showed that the current standards should perhaps be in excess of that which is currently being used. Given the reduced flexibility of internal subdivision on smaller ships, it was assumed that this would be the most challenging increased standard to achieve. In order to validate that the outputs of the cost benefit analysis can be achieved, a study looking at the feasibility of achieving an increased standard was undertaken. A 15% waterline damage length is deemed the most appropriate starting point to align with the current standard for larger vessels and to avoid a step change between small and large ships' damage extents. It is perhaps also conceivable to say that naval vessels are 10 times less likely to have an accident than their mercantile counterparts which would result in a 15% damage extent.

3. Design Implication of a 15% Waterline Length

3.1 Approach

A study was conducted to investigate the degree of design change required to existing in-service naval vessels below 92m in order for them to comply with a 15% longitudinal damage extent. The vessels selected for the study range from 50m to 90m and have commissioned dates ranging from 1979 through to 2003. As such the vessels selected span a range of sizes and ages all of which must comply with a current two compartment standard.

Damage analysis was conducted using the naval architecture design and analysis software Paramarine and making use of the MOD recommended Damage Template functionality which semi-automates the process of applying damage to a vessel. The ships were considered in both a deep and a light condition for all damage cases in order to capture the worst case combination of damage case and loading condition. The damage extent was set to 15% and the location of the damage templates was defined working forward to aft and then aft to forward with the forward or aft face being placed 0.001m in front and behind of each transverse watertight bulkhead respectively (Fig 1). This approach ensured that the maximum number of bulkheads were breached by the damage extent and that correspondingly the worst case damage location was likely to be included in calculations.

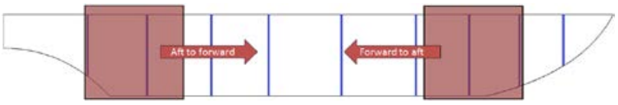

Fig. 1 - Application of damage templates

Damage was simulated at three transverse extents measured as a fraction of maximum beam (B); damage to but not including the centreline (B/2), damage to 20% of the maximum beam (B/5) and full symmetric damage (B). In all asymmetric cases the damage penetration is measured relative to the vessel outer shell at the longitudinal position being examined. Damage was applied to both Port and Starboard sides to identify the worst case scenario arising from design asymmetry.

Two independent assessments of the small ship designs were conducted: The first of these investigated the required change to basic ship vertical centre of gravity (VCG) required to comply with DefStan 02-900 damage stability GZ criteria following 15% damage. This information illustrates the level of ballasting or liquid loading restrictions which would be required in order to ensure that the existing vessel can pass damaged stability criteria with a 15% damage extent applied.

Secondly, subdivision changes were considered in order to achieve compliance. During this process it was felt important to limit the design changes as far as possible so as to minimize deviation from the original design intent and balance. To achieve this, local changes to subdivision were employed first, followed by global changes only where local changes did not result in compliance with damaged stability criteria. The following steps were considered to be local subdivision changes and are listed in the order in which they were applied:

- Increase the height of down-flooding points where practical
- Change tank and void layout to reduce asymmetry whilst maintaining tank volumes as per the original design
- Movement of small internal watertight boundaries

If the above process failed, the global subdivision would be examined and altered until compliance was achieved. This process is outlined below:

- Identify the zones which represented the most onerous stability cases when damaged and investigating small adjustments to the bounding watertight bulkheads
- Investigate global changes to the position of the transverse watertight bulkheads throughout the design whilst maintaining volumes in key functional spaces
- Investigate increases in key characteristics (length, beam depth etc.) to allow compliance with damaged stability criteria

3.2 Assumptions

In order to reduce the complexity of the analysis a number of assumptions were made regarding the nature of the applied damage. These assumptions are seen below:

- Worst case damage is assumed to occur at one of the three transverse extents examined, no additional worst case damage scenarios, unique to each damage location were identified. This includes additional trapped buoyancy cases. The assumption being justified by the expectation that individual cases such as these could be dealt with by adjusting the local design detail, e.g. intentional down-flooding, openings designated ‘to be left open following damage’ etc.
- Vertical damage extent was modelled as full, i.e. no lesser vertical extents were considered.
- Intermediate flooding cases were not considered, where intermediate refers to partial flooding of compartments as a result of non-watertight boundaries (rated to a 1m pressure head) retaining fluid for a short period of time.
- Worst case damage scenarios where non-watertight subdivision completely withstands flood water were not considered.

3.3 Findings

It was shown that the four vessels considered in this analysis can all meet DefStan 02-900 damage criteria with a 15% longitudinal damage extent applied without the requirement for major changes to vessel principal dimensions. Two of the classes considered required changes to internal subdivision in order to comply with the standard however it is important to note that neither sets of changes involved the movement of major transverse bulkheads or global changes to the vessels dimensions.

Where changes to subdivision were necessary these were predominantly centred on reducing the magnitude of flood water asymmetry. In most cases, the driving load condition was seen to be light seagoing, consequentially the arrangement of water ballast tanks to be outboard of fuel oil tanks dramatically reduces the contribution of the fuel oil tanks to floodwater transverse centre of mass (Fig. 2). In all cases B/5 or B/2 damage were seen to constitute the worst case transverse extent and rearranging the transverse location of tanks was seen to significantly improve stability following damage.

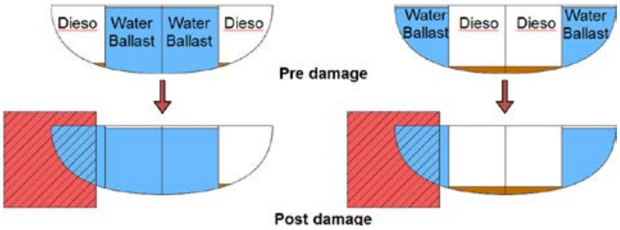

Figure 2 - Layout of water ballast and fuel oil tanks

The configuration of void spaces was found to impact damage asymmetry; a number of instances of asymmetry in void spaces, particularly below machinery spaces, were found to drive poor stability following damage. The rearrangement of these voids, whilst maintaining the functionality of pipe and cable runs, in order that they had minimal transverse subdivision was seen to significantly improve damaged stability (Fig. 3).

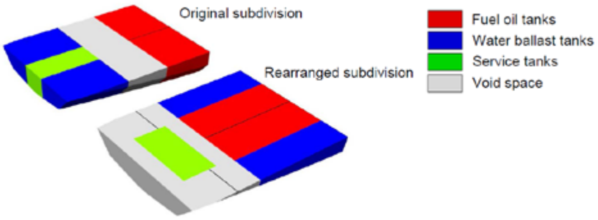

Figure 3 - Arrangement of void spaces

The most substantial changes to internal subdivision were required when compartments above the damage control deck were not subdivided by watertight boundaries. This situation lead to longitudinal progressive flooding and excessively large damage cases causing widespread criteria failure. This issue was found to be the case with one of the classes examined. Almost all other bulkhead changes were confined to the tank top primarily concerning void spaces, fuel oil and ballast tanks. Where tanks were rearranged the overall fluid volumes were maintained as closely as possible to those in the original design.

In all four of the vessels examined compliance was reached with the proposed 15% standard without the requirement for changes to vessel size. The smaller vessels were found to require little or no change to their subdivision to achieve compliance. Both of the larger vessels required local changes to subdivision in way of tank and void space arrangements. Furthermore downflooding points were seen to significantly impair the ability of the designs to meet stability criteria by truncating the damaged GZ curves. It was found that in most cases this effect was completely removed through raising downflooding points by small amounts, with little impact on the overall design.

The relative damage stability performance of the vessels in question can be best examined by converting the two compartment standard to an equivalent percentile damage length for each vessel. The percentile damage lengths can then be compared to the proposed 15% damage lengths. In Fig. 4 the average damage length for each of the vessels has been plotted along with error bars representing the maximum and minimum damage lengths represented by the current two compartment standard. For each zone the damage length was calculated as the maximum length beyond which a three compartment damage scenario would result. The maximum and minimum values of these resulting damage lengths were then calculated and plotted. In the figure we can see that the average two compartment damage length of the two smaller classes are close to the 15% damage extent line with the error bars falling either side. This shows that the increase in damage length is unlikely to require significant, if any, changes to the current design, as was borne out in the results of the analysis. Conversely the proposed 15% extent represents a significant increase in damage capability over current standards for the larger vessels where the average and maximum two compartment damage length was seen to be significantly below the proposed 15% extent, a hypothesis which was also borne out by the significant changes to subdivision required in order for these vessels to achieve compliance.

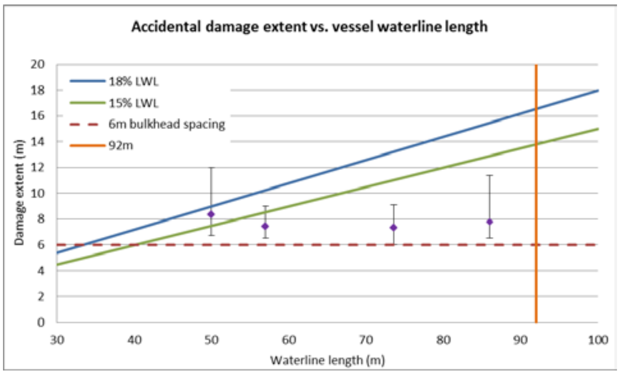

Fig. 4 – Accidental damage extent vs. vessel waterline

From the analysis conducted it is clear that not only is it possible to pass a more onerous 15% damage extent criteria but it is relatively easily achieved and in many cases does not impact the ship significantly. As mentioned previously the one exception to this conclusion is the case in which the damage control deck required the addition of watertight bulkheads. It is unlikely that the additional bulkheads will affect individual compartment volumes and may not significantly affect layout. However the changes proposed may have a detrimental effect on the ability of the crew to move through the ship, but this is considered in line with current naval design convention.

4. Conclusions

The sensitivity study outlined in this paper has shown that despite the subjective nature of some of the cost inputs and the difficulties faced in their estimation, the output of the cost benefit analysis does not vary greatly with variation of key inputs. Furthermore, the lowest calculated value of optimum accidental collision damage extent over the range of inputs examined is seen to be greater than current standards, suggesting that even with the accepted uncertainty in the calculation the current standards fall below the most cost effective extent. In the case of small vessels, the results of the cost benefit analysis suggest that a damage extent of 18.1% represents the most cost effective solution for a vessel less than 92 metres in length. That being said it is important to assess the findings and conclusions in the context of the global ship design and its affordability. It is worth bearing in mind that for any procurement project there is an ultimate maximum price that can be borne and as such further gains in benefit cannot necessarily be realised due to their cost. Furthermore there are numerous tradeoffs that must be addressed throughout the design of a naval combatant and ultimately decisions may have to be taken which would see survivability move away from the optimal damage extent in order to achieve a required capability elsewhere in the design.

Based on these findings, the adoption of a 15% accidental longitudinal damage extent, in line with vessels over 92 metres in length is not conceptually extreme and is a valid assessment point.

Individually, none of the design changes made to the current vessel designs in order to achieve compliance with a 15% damage extent represented significant or costly alterations nor were they revolutionary in terms of small combatant design. It is also notable that none of the vessels examined required changes to the global subdivision in order to obtain compliance, with the most significant changes being damage control deck subdivision. Interestingly only one of the vessels examined required the addition of watertight bulkheads and only on one deck. This could imply that the assumed correlation between damage extent compliance and the addition of transverse watertight bulkheads is more complex than accounted for in the research to date. With that said there is no question that a correlation exists however it is likely to be a stepped relationship, with each step representing an additional watertight bulkhead, and in the analysis to date a significant step has not been encountered.

The comparison of a two compartment standard and a 15% LWL standard demonstrates that vessels closer to the 92 metre delineation will see the largest increase in equivalent damage extent and this is borne out in the results of the design study.

It is clear that in terms of the four vessels examined, the answer to whether a vessel less than 92 metres can meet a 15% damage extent without significant cost is a resounding yes within the limitations of the analysis presented in this paper.

Acknowledgments

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