# Implementation of A Novel Federated Approach to the Analysis of Sinking Ships

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**Synopsis**

This paper presents a summary of the development activities undertaken as part of the refinement and implementation of a new, federated analysis of sinking ships first presented at INEC 2020. The described approach uses a functional survivability analysis as the basis to generate a time domain sinking ship assessment and subsequent escape and evacuation analysis. The result of this approach is a time to sink based on a realistic input threat against which an escape time is generated using the same damage inputs and taking account of the environment and damage induced restrictions in the flow of evacuees. The approach is designed to replace fixed and empirically derived escape criteria with realistic scenario-based assessments which cover the range of likely threats leading to abandonment.

The methodology used leverages state of the art escape and seakeeping software using a survivability software model at its core. Results are driven by a large number of inputs for each software stage, all of which determine the complexity of the input modelling required and the processing time of the analysis. A sensitivity study has been conducted on an in-service Royal Navy platform and the results are summarised. The impact on assessment implementation is then discussed.

The practicalities of using the methodology to conduct whole ship assessments of naval platforms is further discussed. Through the conduct of this most recent study, a number of advancements and opportunities have also been identified and are presented.

Keywords: Escape and Evacuation, Vulnerability Assessment, Damaged Stability, Time to Escape, Sinking Ships, Time Domain Seakeeping Assessment, Carpet Plot, Naval Ship Certification

## 1. Introduction

Previous work conducted by the authors (Goddard, R. et al., 2021) proposed a novel approach to the analysis of sinking ships, combining the time domain analysis of realistic sinking conditions based on actual threat weapons with a time domain escape and evacuation analysis. This federated approach leveraged advances in the state of the art of seakeeping, survivability and escape and evacuation tools to automate the generation of highly complex damage analysis and associated escape scenarios. In doing so, a new method of assessing the escape and evacuation performance of a ship was implemented, where time to escape could be compared to associated time to sink across a large number of realistic damage scenarios.

This work has been developed further over the last year, targeting sensitivities of key inputs and applying the methodology to an in-service warship; the Royal Navy's Type 45 Destroyer.

**Author's Biography**

**Rick Goddard** is a chartered engineer, he has a background in stability certification, derivation of standards and advanced intact and damaged seakeeping analysis. Rick has experience of working on in-service support projects as well as concept designs. Amongst his previous employments, Rick worked in the Naval Authority stability section.

**James Schofield** is Managing Director of Survivability Consulting Limited. He has over twenty years' experience in naval vulnerability, having been involved in the design assessments of Type 45, QE Class, Type 26, MARS Fleet Tanker, Fleet Solid Support and Type 31e. He leads SCL's development of the Purple Fire tool.

**Dr David Menzies** is a Principal Engineer at Survivability Consulting Limited. He has worked on the vulnerability of a number of platforms and also completes much of SCL's missile lethality work. He leads SCL's integration and use of the links between Purple Fire, maritimeEXODUS and FREDYN.

**Steve Marshall** is the Head of Ship Hydromechanics in the Naval Authority Group, UK MoD. He has over thirty years of experience in Warship and Naval Auxiliary design and, as the Naval Authority for Ship Stability, their Safety Certification.

**Paul Gliddon** is a Principal Naval Architect and Chartered Engineer with experience in stability assessments of both naval and commercial vessels from concept through to build and in service support.

**Harry Thompson** is a naval architect and associate member of RINA. Harry has worked on numerous time domain seakeeping projects and prior to joining Steller Systems received a Master's degree in Naval Architecture from Newcastle University where he completed the thesis "Seakeeping Analysis of a High-Speed Search and Rescue Craft and the Study into the Effects of Trim Tabs."

## 2. Overview of approach

Under the derived approach, dynamic seakeeping tools are used to assess the ultimate stability of combatants, using blast, fragment, shock and whipping damage calculated in a vulnerability assessment to define damage openings. The calculated flood water progression and vessel survival/loss is used to inform the vulnerability assessment which in turn automates the modelling of escape and evacuation routes more accurately. The escape and evacuation analysis subsequently uses the vessel motions and flood water progression from the dynamic seakeeping analysis to remove or alter escape routes according to flood water and blast/fragment damage and the final escape times are then assessed against the actual time to sink calculated from the seakeeping analysis.

Seakeeping analysis is conducted using the Collaborative Research Navies developed tool FREDYN, escape and evacuation assessments are conducted using Greenwich University's maritimeExodus (mEX) and generation of threats, associated damage and damage openings generated using Survivability Consulting Limited's Purple Fire. The Purple Fire tool is used to automate the generation of highly complex FREDYN damage scenarios and to read the results and use them to create escape and evacuation models and alter them in the time domain dependent on flood water denial of escape routes.

A large number of ultimate stability damage cases can then be assessed, aligning with the extents represented in a traditional naval carpet plot. The subsequent escape times and times to sink can be used to append the plot to represent a new escape and evacuation carpet plot.

This approach would hitherto have been considered too computationally complex to undertake, however developments in the Purple Fire tool and in the workflow between dynamic stability analysis, vulnerability assessments and escape and evacuation simulations means it is now possible to conduct analysis of this kind across the range of damage scenarios typically seen in a carpet plot, improving on the current escape and evacuation approach of considering three cases based on static stability assessments.

The flow chart in Figure 1 presents the process employed and highlights the validation activities associated with the overall analysis. Validation remains a critical part of what is otherwise a highly automated process; the core of this uses a static stability model to assess near-sinking cases which are recreated in FREDYN.

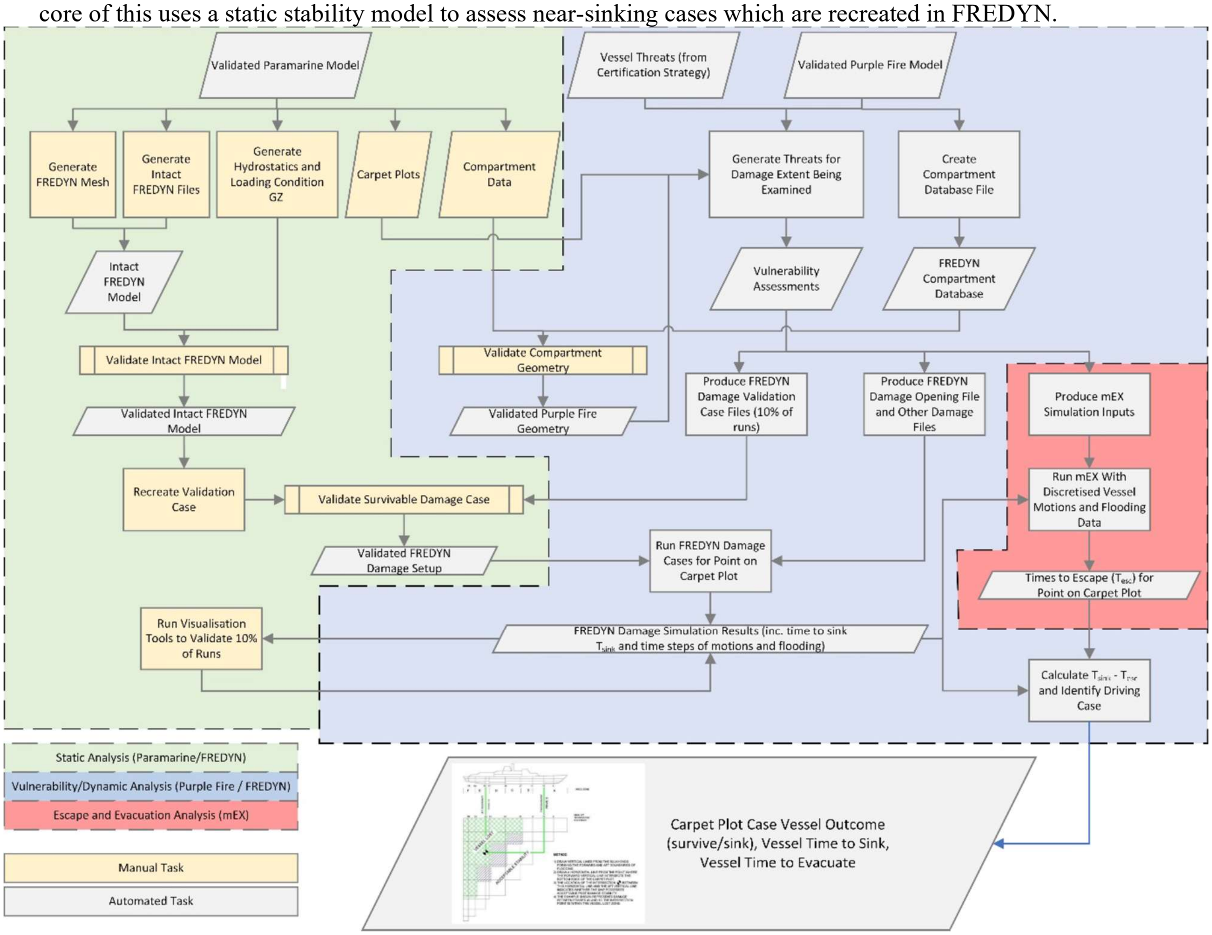


Figure 1: Process Flowchart

## 3. Refinement & Use of approach

Recent work has been undertaken to refine the approach and conduct its first use on an in-service warship. This covered three areas:

1. Configuration and Verification of the Purple Fire Type 45 Model: The setup of the Purple Fire Type 45 model for all of the assessments required in the project and the testing of a range of simulations using the existing default FREDYN and mEX parameters.
2. Implementation of the ability to vary the required Parameters: so that Purple Fire can automatically vary existing default FREDYN coefficients for discharge/leaks/collapse etc., and certain mEX parameters such as crew speeds in flooded situations. This also explores parameter sensitivities and derives the best practice for future modelling.
3. Initial Consideration of Type 45 Damage Cases and Sensitivities: There are a number of parameters to which federated results could be sensitive, or which need to be considered as bounds of the analysis (in that the results are certainly sensitive to them but for which parameters must be defined for future assessments). Initially a subset of parameters is examined to give an indication of whether and when variation in sinking or escape times could be seen.

## 4. Validation of models

Integral to the success of this work is the detailed validation of both the input and output data to confirm alignment between the generated Purple Fire and the supplied Paramarine model, as well as alignment with customer supplied information. The approach involves a full review of the watertight integrity definition, checking modelling of all buoyant structure and freeflood spaces including vessels superstructure, and the modelling of dummy tanks to recreate asymmetry in the buoyant hull envelope which cannot be captured in FREDYN purely with a mesh. In terms of the process, firstly the intact hull is validated before then going on to validating individual damage cases. Intact validation consists of progressively checking the following three areas;

1. Overall hullform using a simplified model with no tanks and comparing the GZ data, LCG and displacement outputs from both software programs.
2. Tank database and internal sub-division generated from the hullform by Purple Fire, achieved by direct comparison of the tank database files to equivalent files generated by Paramarine.
3. Individual loading conditions using equilibrium drafts, heel and GZ data output from both software programs.

The damage validation process takes the form of GZ and equilibrium draft assessment, alongside the examination of damage analysis using visualisation of flood spread through time extracted from FREDYN. The flooding files used by FREDYN are output from Purple Fire and used to create a replicated damage case within Paramarine. Any deviations between equilibrium drafts, list and GZ data outputs from both software programs are identified.

The main residual source of differences found in the Type 45 process, once various discrepancies had been harmonised, were simplifications made in the Paramarine model where multiple compartments are modelled as one space compared to the Purple Fire model which considers all boundaries.

Overall, the process of validating a small number of intact and damage cases gives the confidence that good alignment between models is being achieved later in the process. Validation damage cases are selected which give a high degree of coverage of the internal subdivision of the ship.

## 5. Sinking Criteria

The originally intended method was to align with the existing definition for ‘ship loss’ by creating an extreme damage case in Paramarine until it failed quasi-statically. Interestingly it was not possible to create such a case, with the ship exhibiting high reserves of buoyancy when sustaining hostile damage within reasonable extents. therefore a new approach to defining a ‘ship loss’ was required. Firstly, a maximum heel and trim criteria was explored, using the current values in MOD guidance. The robustness of these values when it comes to defining a vessel as lost are questionable as they still do not provide a clear-cut definition and fail to take into account diminishing freeboard.

It was decided to use a series of motion sensors within FREDYN at certain locations along the length of the vessel, both port and starboard on 1 deck. Motion sensors within FREDYN can output a ‘wave height’ relative to their position, and therefore a vessel can be considered lost when any of the sensors becomes submerged (equating to a zero or negative freeboard condition). This approach removes vagueness from the existing heel and trim criteria whilst also providing a ship-specific method where sensors can be placed at critical locations. The locations of these sensors could potentially be derived from time domain assessment of water levels at escape and evacuation points with ship lost criteria corresponding to the point at which a predetermined fraction of these become inoperable.

Beyond the definition of sinking, there remains the issue of identifying the particular combination of threat and detonation locations which will generate sufficient damage to cause the vessel to sink. From a stability point of view, “damage” amounts to the complete opening of given watertight zone(s) to flood water. However, in vulnerability assessments the damage spread is determined by the structure lost due to damage mechanisms (e.g. blast, shock) within the vessel. This itself, is highly dependent on the detonation location, which is further dependant on the fusing logic of the threat, etc. Often this damage will be highly idiosyncratic and will not resemble the necessarily more abstract damage shown on carpet plots.

The initial method employed relied on using the carpet plots in concert with the Paramarine model to identify flooding extents which would lead to a sinking case. However, as pointed out above, carpet plot damage cases did not lead to quasi-static sinking in the Paramarine model. Consequently, additional work was required to identify such cases. This necessitated an additional parameter space in Purple Fire which varied threats, number of hits and hit location.

The first point to note is that reassuringly, none of the threats considered were capable of reproducing primary damage levels seen in a carpet plot with a single shot. This followed from comparison of the blast spread in Purple Fire runs comparted to the damage required by the carpet plot. Consequently, single hit simulations with FREDYN were not run and multiple consecutive shots were a necessity. This process tried to be mindful of the trade-offs between achieving carpet plot damage required for sinking while not completely obliterating the vessel and making any evacuation assessment pointless.

After running this parameter space, a set of large threats were identified actually capable of exceeding the carpet plot sinking criterion. Even for these threats, multiple hits were required to achieve this. From these extreme cases, three were selected as candidates for the parameter variation.

## 6. Sensitivity Study

There are a large number of input parameters to which FREDYN results in particular could be sensitive. Many of these are not significant to typical seakeeping assessments, but the use of the tool in highly complex sinking cases where substantial flooding through all types of structure and through significantly greater volume of openings could occur requires that they be examined.

Table 1 below summarises the full list of parameters in the FREDYN and mEX input files which are considered to be either variable or constants that require examination in the context of large scale damage simulation. The table also gives a potential range for variation and indicates whether each was considered as part of the sensitivity study. Note that this initial study only considered a subset of the sensitivities, the others will be addressed in future work.

Table 1: Summary of Parameters

| **Parameter/Sensitivity** | **Range** | **Studied to date?** |
|---|---|---|
| Minor Structure Permeability | 5%-40% | Yes |
| Minor Structure Discharge Coefficient | N/A | No |
| Minor Structure Collapse Pressure | 0.1m-upwards | Yes |
| Non-WT Structure Permeability | 5%-40% | Yes |
| Non-WT Structure Discharge Coefficient | N/A | No |
| Non-WT Structure Collapse Pressure | 1.0m-upwards | Yes |
| WT Structure Collapse Pressure | N/A | No |
| Pressure differential at which a door cannot be opened | Head difference of 0.3m – 1m | No |
| Door Discharge Coefficient | N/A | No |
| Non-WT Door Permeability | N/K | No |
| Blast Door Collapse Pressure | N/A | No |
| WT Door Collapse Pressure | N/A | No |
| Non-WT Door Collapse Pressure | N/A | No |
| Escape Hatch Collapse Pressure | N/A | No |
| Leakage of external opening covers | N/K | No |
| Wave Height | Mean SS2-SS6 | Yes |
| Wave Period | Mean SS2-SS6 | Yes |
| Wave Gamma | N/A | No |
| Wave Direction | 0°-180° | Yes |
| Freeze Yaw | True/False/ False with springs | No |
| Vessel speed | N/A | No |
| Linear Roll Damping Factor | N/A | No |
| Quadratic Roll Damping Factor | N/A | No |
| Added mass and diffraction database (input file used by Purple Fire, generated by Steller characterised by input draughts for sinking vessel) | Intact Draughts – Draught just prior to vessel loss. | No |
| Opening Strip Height | N/A | No |
| Opening Strip Width | N/A | No |
| Horizontal Opening Height Ratio | N/A | No |
| Horizontal Opening Div Ratio | N/A | No |
| Pressure Correction Tolerance Max | N/A | No |
| Pressure Correction Tolerance Min | N/A | No |
| Pressure Correction Tolerance Ratio | N/A | No |
| Rise Tube Full Factor (depend on displacement) | N/A | No |
| Rise Tube Area Factor (depend on displacement) | N/A | No |
| Rise Tube Volume Factor | N/A | No |
| Abandon Initiation Time | N/A | No |
| LSA Limit Angle | N/K | No |
| LSA Preparation Time Factor | N/K | No |
| LSA Travel Time Factor | N/K | No |
| Crew Speed Factor (for different volume fractions) | 0.5-1.0 | No |
| Crew MII Time | N/K | No |
| Number of watertight doors in transverse bulkheads left open | No doors open, ½ doors open, all doors open | Yes |
| Level of modelling definition in non-watertight structure | Simple-Full | Yes |

The set of parameters indicated for study during the recent work led to a large number of combinations for simulation, the results of which were then examined for variation with each particular parameter.

Whilst detailed results cannot be presented within the scope of this paper, a subset of the time to vessel loss results is given in Table 2 as an indication, in terms of the relative changes in time for some of the parameters (averaging over all other parameters). A negative change is a reduction in time to vessel loss caused by the change in parameter indicated.

Table 2: Summary of Results

| Parameter/Sensitivity | Change | Stern Case | Bow Case | Heel Case |
|---|---|---|---|---|
| Minor & non-WT Structure Permeability | 5% to 40% | -16% | -12% | -1% |
| Minor & non-WT Collapse | None to V-Line | -4% | -32% | -21% |
| Wave Approach Direction | Stbd to Stern | +136% | +245% | +255% |

Unsurprisingly, allowing greater flooding through, and collapse of, types of non-watertight structure causes faster sinking but to significantly different extents for the different damage cases.

In all cases waves from the stern take longer to cause vessel loss than starboard beam seas, but again the relative change is very dependent on damage case.

These indicative results, along with the others identified in the study assisted in the identification of inputs for which a more detailed assessment of appropriate value is required.

## 7. Practicalities & Lessons

### *7.1. Lessons on Model Complexity*

Initial estimates of likely run time of the coupled simulations have proven to be optimistic. This is largely a result of the level of complexity inherent in Purple Fire models which are more detailed than manually generated FREDYN and mEX models. The complexity of the real warship model was much greater than in previous use of the approach on concept designs and commercial ships.

For example, the Purple Fire FREDYN link generates Type 45 FREDYN damage cases which have an order of magnitude more flow paths (i.e. flooding routes between floodable spaces) than those usually manually generated when doing FREDYN simulations. Moreover, the level of compartmentalisation of Purple Fire models goes beyond the WT boundary level typical of Paramarine models, which leads to a considerably larger number of spaces.

Similarly, the complexity of mEX models generated from Purple Fire for naval platforms are likely more complicated than the typical commercial maritime craft. The large number of WT doors, vertical links between decks and designated compartments (currently required to allow primary damage denial of routes) add to complexity and require more computational resources. This, together with the additional scripting commands executed at run-time require more time to complete. The requirement to run multiple iterations of each abandonment to obtain the relevant statistics further increases the required time to complete simulations. This is compounded by issues trying to run excessive mEX instances simultaneously, thereby nullifying any advantage of processor systems with large numbers of cores. This latter limitation of SCL's approach and implementation is being explored with the University of Greenwich. Also being considered is the ability to run mEX in an output-limited mode to lower the time take to write files at the end of each run and to open life rafts based on conditional outcomes (e.g. when a crew member person reaches the raft).

Whilst the overall calculation times are higher than initially predicted, ongoing work seeks to reduce calculation times in the escape and evacuation portion of the analysis as does investigation of the sensitivities around the seakeeping analysis. In all cases, the real benefit of the analysis type, in respect of man hours of calculations, is still realised, with the calculation time being made up exclusively from computational time which is not human resource intensive.

### *7.2. Lessons on Identifying Sinking Cases*

Another issue observed during the work was the difficulty of relating weapon threat damage extent to a carpet plot damage footprint. In particular, there is no current easy method in Purple Fire of identifying the threat/hit location/number of hit combinations that are capable of realising a given carpet plot damage case. This was done in an ad-hoc exploratory fashion using Purple Fire's batch capability.

However, SCL envision a new search mode in Purple Fire where the user specifies:

- A list of threat weapons;
- A grid of possible attack locations to test;
- A damage case (carpet plot or otherwise) to achieve.

Purple Fire would then conduct a search and output all the possible threat engagements to realise this damage case. This could be used to derive a metric which quantifies the risk the damage case actually poses. However, it is important to know on what basis the carpet plot cases were originally derived, and relate this to the sinking criteria desired, to avoid excessively extreme damage cases being considered.

### *7.3. Lessons Verifying Purple Fire Against Paramarine*

During the process multiple lessons have been learnt including a new methodology for validation and improving outputs to establish a quicker way to reproduce damage cases in Paramarine amongst others. The key lessons are summarised as:

- Upon start-up highlight differences in compartmentation between the models. This is to ensure any simplifications made to the Paramarine model are captured and which compartments are affected are understood.
- Capture non-standard flooded permeabilities ensuring models align. This is essential as some simplified spaces in Paramarine which contain a variety of compartments will have a single permeability which differs from the standard values and the Purple Fire model.
- If there remain significant areas of simplification within Paramarine compared with the Purple Fire model, it is recommended that smaller, but complete zones are damaged during the validation process in line with the failing cases on the carpet plot (previously generated in Paramarine). This is a more controlled method when identifying compartment errors, such as incorrect volumes or permeabilities. This method would still result in more extreme asymmetric damage cases being validated, but only after more simplistic damage cases have been checked.
- Setting up the extreme damage extent cases within Paramarine is highly labour intensive and therefore time consuming to ensure that it accurately represents the Purple Fire damage. Creation of an interface between Purple Fire and Paramarine could allow automatic creation of the damage summary within Paramarine, solving the issues highlighted and further increasing the accuracy of the Paramarine damage representation. Such an interface would require the differences in subdivision between the Purple Fire and simpler Paramarine model to be identified and completely understood.
- Further refinement should be made to the existing motion sensor approach. The location both vertically and horizontally should be reviewed to accurately define ‘vessel lost’ criteria. It is proposed that the locations should be advised by the Naval Authority Group at the start of each project.

## 8. Summary

The Purple Fire Type 45 model has been updated from its previous state of being suitable for vulnerability assessments to include the accuracy and detail needed for FREDYN and mEX simulations. The model has been verified and Purple Fire’s automated links have been tested. Lessons have been taken from the time taken to configure the model against a Paramarine datum, and processes and tools put in place to speed this up for other classes.

The existing links from Purple Fire to mEX and FREDYN have been enhanced to allow user-configuration of the large number of parameters that could affect results for sinking time and abandonment time. An initial demonstration showed variation in ship motion and flooding for a small number of parameters.

Previous use of the approach on a commercial ship and a concept Frigate (at fairly low detail) achieved some successful results with a sinking criterion based simply on capsize, although, with hindsight, there were some cases where sinking did not occur which suggested that a more complex criterion was needed.

This was the case for the Type 45 runs, and it was discovered that it was impossible to identify threat-based damage cases which resulted in a vessel lost condition. This was further reinforced when attempts to generate sinking cases within the Paramarine model were also not possible. As a consequence, and through discussion with the Naval Authority, a definition of vessel lost was agreed for the purposes of the study whereby specific locations on the weather deck were monitored and when submerged, the vessel was deemed lost. This allowed the main simulations for the task to proceed. These covered three extreme damage cases with variation of more parameters than in the initial demonstration. The variation of parameters did exhibit variation of sinking times, showing that before the federated approach can produce real advice, values for these parameters must be agreed.

By far the most important conclusion to this work is the requirement for a suitable definition of “vessel lost”. The current approach assumes the submergence of any one of various key locations on the vessel. However, adopting this definition, combined with the significant level of battle damage that must be inflicted on the vessel to achieve an indicative carpet plot damage case, results in very rapid sinking times which preclude the possibility of mounting a complete abandonment of the vessel.

Also of key importance is that achieving carpet-plot level damage cases is very difficult from a threat-based scenario. This study showed that multiple consecutive hits from large threats, scenarios way beyond what is normally considered in vulnerability modelling, were required to approximate the requisite damage case.

As a result of these difficulties, various good practices and solutions have been identified which should be used when this method is applied to other vessels. These will ensure the verification process proceeds more rapidly and smoothly than has been the experience for this vessel.

It is important to stress that it is not the place of this work (now or in the future) to suggest a vessel loss criterion. Equally important is an identification of the point at which a call to abandon is to be made. This must be decided by the Customer based on “real world” considerations, independently of the FREDYN and mEX simulations, as to do otherwise would simply allow the federated method to decide its own success criteria.

It is expected that once criteria are decided for the start of abandonment and the point beyond which abandonment would be deemed unsuccessful, and once the FREDYN and mEX parameters have been quantified, longer simulations will be able to show progressive sinking cases from less severe primary damage cases.

## 9. Future Steps

Having identified sensitivities to inputs to the federated analysis, work is now needed to identify appropriate values. It is anticipated that factors such as collapse pressures will be assessed using a combination of ship surveys and Finite Element Analysis (FEA) to determine typical collapse pressures for different bulkhead types. Inputs such as leak area ratio can be determined for typical non-watertight bulkheads through survey using techniques such as ultrasonic testing, traverse times in semi-flooded passageways can be determined through literature studies and through testing in facilities such as the royal navy damage repair and instructional unit. Analytical or experimental assessments could be designed and conducted for each of the identified sensitivities, enabling the production of guidance documentation to support future naval platform assessments.

A body of work is required to derive a pragmatic and realistic vessel lost criteria for naval ships.

Work is additionally required to ascertain an appropriate timeline between damage being incurred and the announcement to evacuate. A working proposal is to form a panel of subject matter experts for each ship being considered, made up of current and past senior officers. The panel would be consulted to understand the decision-making process that leads to the abandonment call and a set of times developed to be used in the escape and evacuation assessment element of the analysis.

## References

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