A Novel Approach to the Analysis of Sinking Ships; Combining Vulnerability, Stability and Escape & Evacuation Simulations

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Synopsis

At present naval ship ultimate stability, Escape & Evacuation (E&E) analysis and operator guidance are largely produced independently. Carpet plots are calculated quasi-statically giving estimates of vessel likelihood of survival using delineations of 'poor stability' and 'vessel lost' to the command whilst the definition of poor stability does not account for the dynamic effect of sea states on vessel motion. With advances in the software used to model threats and resultant ship damage effects, a new approach is proposed whereby abandonment and dynamic sinking are modelled alongside a functional survivability analysis. By integrating and automating survivability analysis with state-of-the-art E&E and seakeeping software, an ultimate stability carpet plot is produced giving times to sink based on time domain seakeeping simulations. In parallel, escape times can be generated including the effects of flooding and ship motions on movement of personnel which are then compared to the calculated sinking times. Through a combined consideration of threat, flooding and ship motions the escape arrangements of a vessel can be understood. It is possible to conduct this combined analysis in a cost and time efficient manner through the use of the tools developed as part of this work

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

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1. Introduction: The need for a combined approach

The process of conducting naval combatant safety assessments, certification and of producing operator guidance is, by necessity, discretised into key hazard areas in reflection of the challenges each area presents. This approach allows areas such as stability, structures, escape and evacuation, vulnerability etc. to be certified independently and for plan approval to be refreshed through vessel life at the periodicity required by each field individually. The output of these activities is then brought together at the point of final certificate issuance.

There are some aspects of vessel safety which are intrinsically linked and which would benefit from a more combined approach to safety evaluation. Of specific interest, the assessment of ship survivability following an extreme damage event and the subsequent vessel behaviour should the damage ultimately lead to vessel loss. The current approach for the key hazard areas of stability, vulnerability and escape and evacuation is presented below:

1.1. Stability

The behaviour of a vessel when experiencing damage beyond design extents is assessed statically and presented in the form of a carpet plot, stating whether the vessel is lost, exhibits poor stability (heel >20° and/or trim >10°) or passes damaged GZ criteria. A further caveat is included stating that engineering judgement of the GZ curve should be included in the process to ensure acceptable reserves of stability are maintained. The majority of defence standards are derived from the work of Sarchin and Goldberg [1962] which assumes a sea state 4, with GZ curve criteria derived correspondingly. Poor stability criteria do not assess the vessel motions beyond 20° as a result of sea conditions and there is subjectivity in way of visual assessments of GZ curves. Dynamic seakeeping tools are beginning to be used to assess factors such as V-line roll and heave allowances (Peters, Goddard, Dawson 2014) however these are not being used in the assessment of ultimate stability at present. As a result, the distinction between ‘poor’ and ‘vessel lost’ cases is limited by static assumptions with little margin for vessel motions. ‘Poor’ criteria are based on the requirement to be able to conduct damage control activities, in fact, these activities are more likely to be limited by vessel motions than by static heel or trim angles.

1.2. Vulnerability

Vulnerability certification uses a probabilistic threat-based approach to the analysis of key vessel functions following attack from a series of defined threats. Tools such as Purple Fire (Schofield JS, 2018) quantify the resulting impact on key vessel systems in the float, fight, move functions and the results are used to conduct design appraisal and vessel certification activities. At present, this analysis is conducted in isolation from ultimate stability assessments and makes assumptions regarding the vessel stability, extent of flooding and subsequent attitude/survivability following damage. Recent developments have seen tools such as Purple Fire integrate with Maritime Exodus (mEX) to generate Escape and Evacuation simulations however Escape and Evacuation is not considered directly in the vulnerability assessment.

1.3. Escape and Evacuation

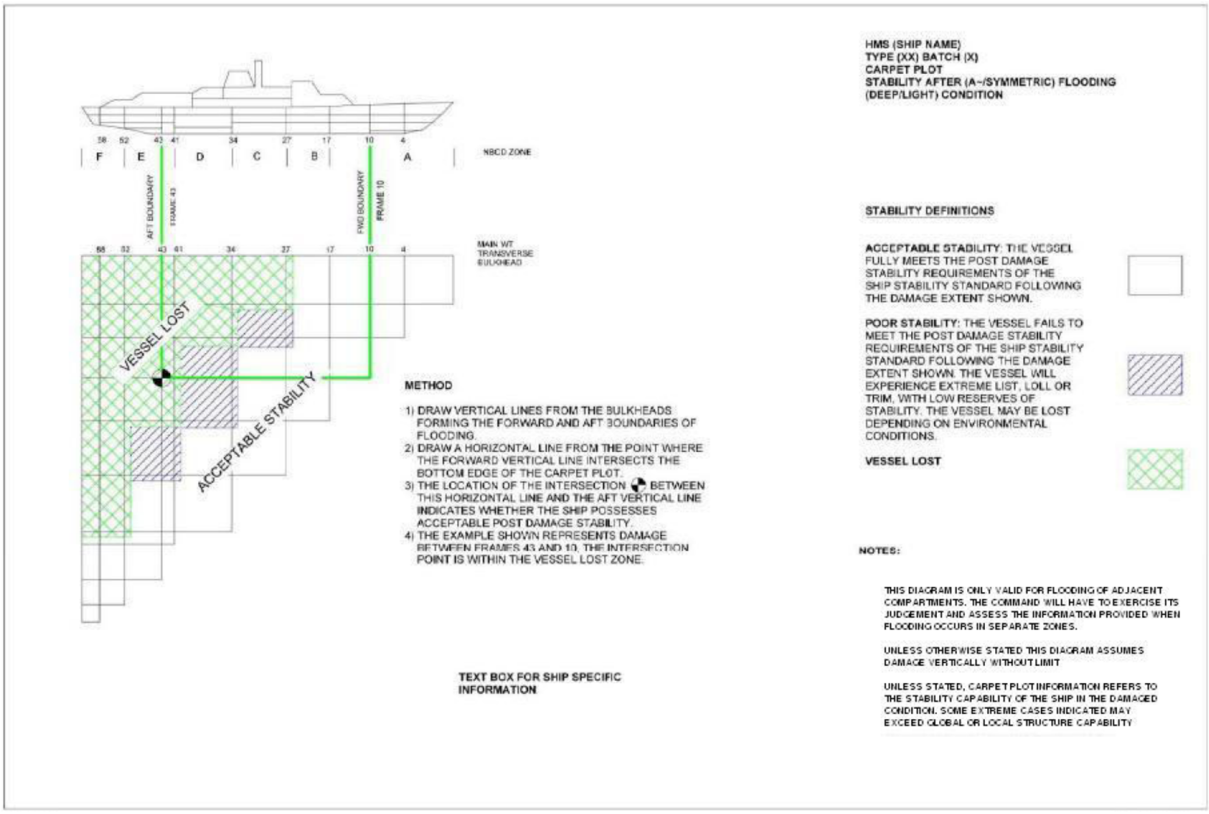
Recent developments have seen the use of probabilistic time-domain escape and evacuation assessments. Escape and evacuation certification requires that the impact of damage on escape and evacuation times is considered as part of the required analysis however at present this is achieved predominantly through application of a static 20° heel and 10° trim vessel attitude and through the selection of three damage cases. Naval certification does not consider the dynamic movement of the sinking ship nor does it consider the denial of escape routes as a result of damage or flooding beyond that initially experienced. Escape times are assessed against a deterministic criterion, not linked to any assumed damage case or associated time to sink. Only three damage cases are assessed as standard making it difficult to ensure that the worst-case probable damage cases are identified. The movement of escaping personnel does not account for the presence of flood water and the impact this may have on transit speed through affected compartments.

1.4. A combined approach – the proposal

It is proposed that the limitations of each of the areas of certification presented can be addressed directly by the analysis being conducted in the other areas. Dynamic seakeeping tools can be used to assess the ultimate stability of combatants, using blast, fragment, shock and whipping damage calculated in the vulnerability assessment to define damage openings. The calculated flood water progression and vessel survival/loss can be used to inform the vulnerability assessment which in turn can model the escape and evacuation routes more accurately. The escape and evacuation analysis can use the vessel motions and flood water progression from the stability analysis to remove or alter escape routes according to flood water and blast/fragment damage and the final escape times can be assessed against the actual time to sink calculated from the stability analysis.

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.

It is proposed that the output of this combined assessment be presented in a carpet plot style format, outlining the stability of the vessel for damage cases beyond the design extent, derived from dynamic damaged ship seakeeping analysis. An example of a carpet plot is given in **Figure 1**, taken from Maritime Acquisition Publication 01-024. The publication should be consulted for further guidance on the generation and background of these plots. This paper seeks to enlarge on the carpet plot approach by additionally giving the escape time and time to sink for each damage extent to inform escape and evacuation certification. The proposed approach can be seen summarised in the flow chart in **Figure 2**.



HMS (SHIP NAME)
TYPE (XX) BATCH (X)
CARPET PLOT
STABILITY AFTER (A~/SYMMETRIC) FLOODING
(DEEP/LIGHT) CONDITION

STABILITY DEFINITIONS

ACCEPTABLE STABILITY: THE VESSEL FULLY MEETS THE POST DAMAGE STABILITY REQUIREMENTS OF THE SHIP STABILITY STANDARD FOLLOWING THE DAMAGE EXTENT SHOWN. ☐

POOR STABILITY: THE VESSEL FAILS TO MEET THE POST DAMAGE STABILITY REQUIREMENTS OF THE SHIP STABILITY STANDARD FOLLOWING THE DAMAGE EXTENT SHOWN. THE VESSEL WILL EXPERIENCE EXTREME LIST, LOLL OR TRIM, WITH LOW RESERVES OF STABILITY. THE VESSEL MAY BE LOST DEPENDING ON ENVIRONMENTAL CONDITIONS. ▨

VESSEL LOST 🟩

METHOD

1) DRAW VERTICAL LINES FROM THE BULKHEADS FORMING THE FORWARD AND AFT BOUNDARIES OF FLOODING.
2) DRAW A HORIZONTAL LINE FROM THE POINT WHERE THE FORWARD VERTICAL LINE INTERSECTS THE BOTTOM EDGE OF THE CARPET PLOT.
3) THE LOCATION OF THE INTERSECTION ◐ BETWEEN THIS HORIZONTAL LINE AND THE AFT VERTICAL LINE INDICATES WHETHER THE SHIP POSSESSES ACCEPTABLE POST DAMAGE STABILITY.
4) THE EXAMPLE SHOWN REPRESENTS DAMAGE BETWEEN FRAMES 43 AND 10. THE INTERSECTION POINT IS WITHIN THE VESSEL LOST ZONE.

TEXT BOX FOR SHIP SPECIFIC INFORMATION

NOTES:

THIS DIAGRAM IS ONLY VALID FOR FLOODING OF ADJACENT COMPARTMENTS. THE COMMAND WILL HAVE TO EXERCISE ITS JUDGEMENT AND ASSESS THE INFORMATION PROVIDED WHEN FLOODING OCCURS IN SEPARATE ZONES.

UNLESS OTHERWISE STATED THIS DIAGRAM ASSUMES DAMAGE VERTICALLY WITHOUT LIMIT

UNLESS STATED, CARPET PLOT INFORMATION REFERS TO THE STABILITY CAPABILITY OF THE SHIP IN THE DAMAGED CONDITION. SOME EXTREME CASES INDICATED MAY EXCEED GLOBAL OR LOCAL STRUCTURE CAPABILITY

Figure 1: Example carpet plot taken from MAP 01-024

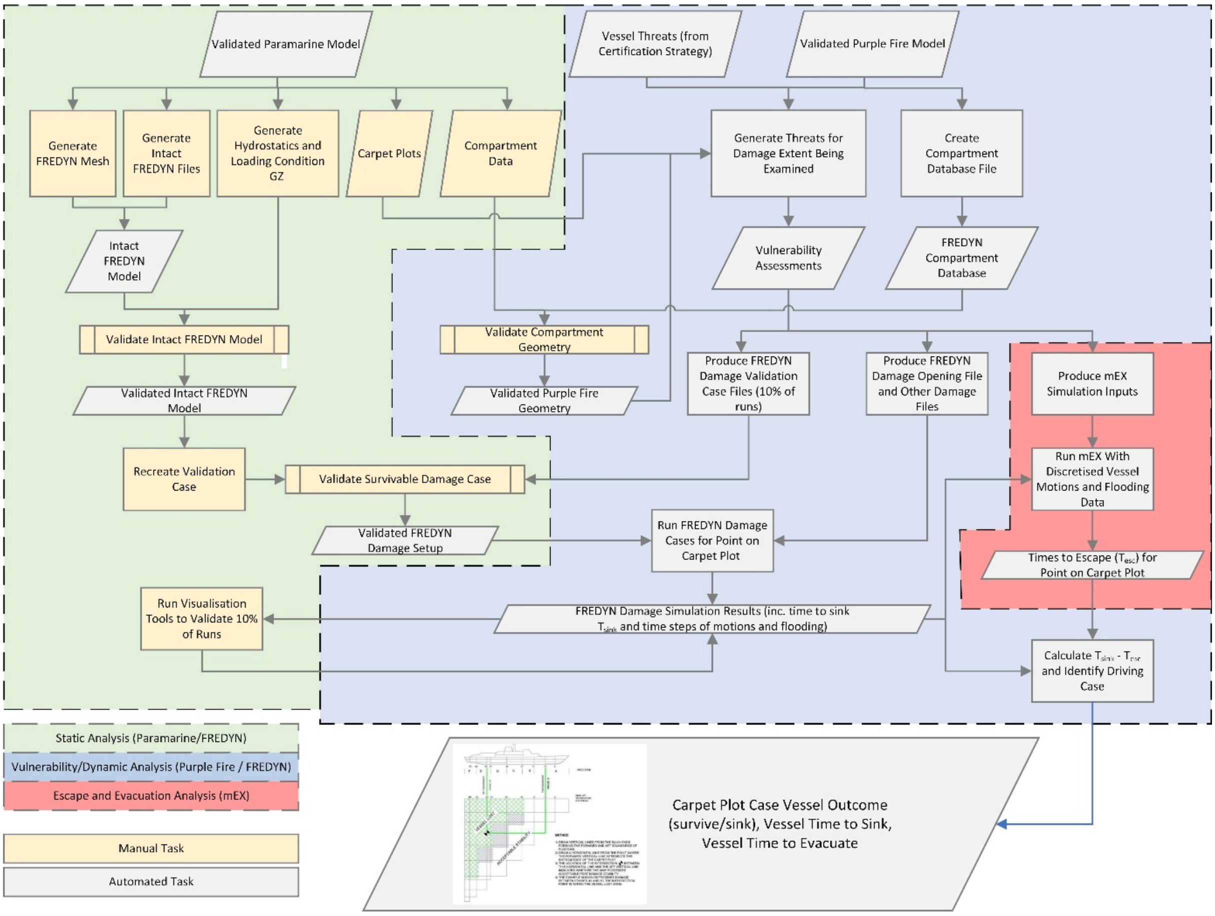


Figure 2: Process Flowchart

2. The test bed: Spartan

In order to test the proposed approach, a naval combatant was required which met naval design standards. The Steller Systems Spartan concept was selected as an example of a low budget modern survivable combatant. The design incorporates a stern ramp, large stern garage and a dedicated UAV hangar. The vessel was designed from the outset with survivability in mind and used a detailed vulnerability model throughout the design process. A static stability model and Purple Fire model were already in existence and these were used as the basis of the analysis, along with a maritimeEXODUS escape and evacuation model created automatically by Purple Fire.

For the purposes of this paper, one loading condition has been considered corresponding to a deep Start of Life (SOL) condition. An overview of the vessel and particulars can be seen in **Figure 3** and a watertight integrity drawing seen in **Figure 4**.

SPARTAN

Length Overall: 117m
Length Waterline: 110m
Beam Waterline: 17.5m
Design Draught 4.1m

Light SOL Displacement: 3028te

Max Speed: 26kts
Endurance at 12kts: 6000nm

Standard Complement: 113

Figure 3: Spartan key characteristics

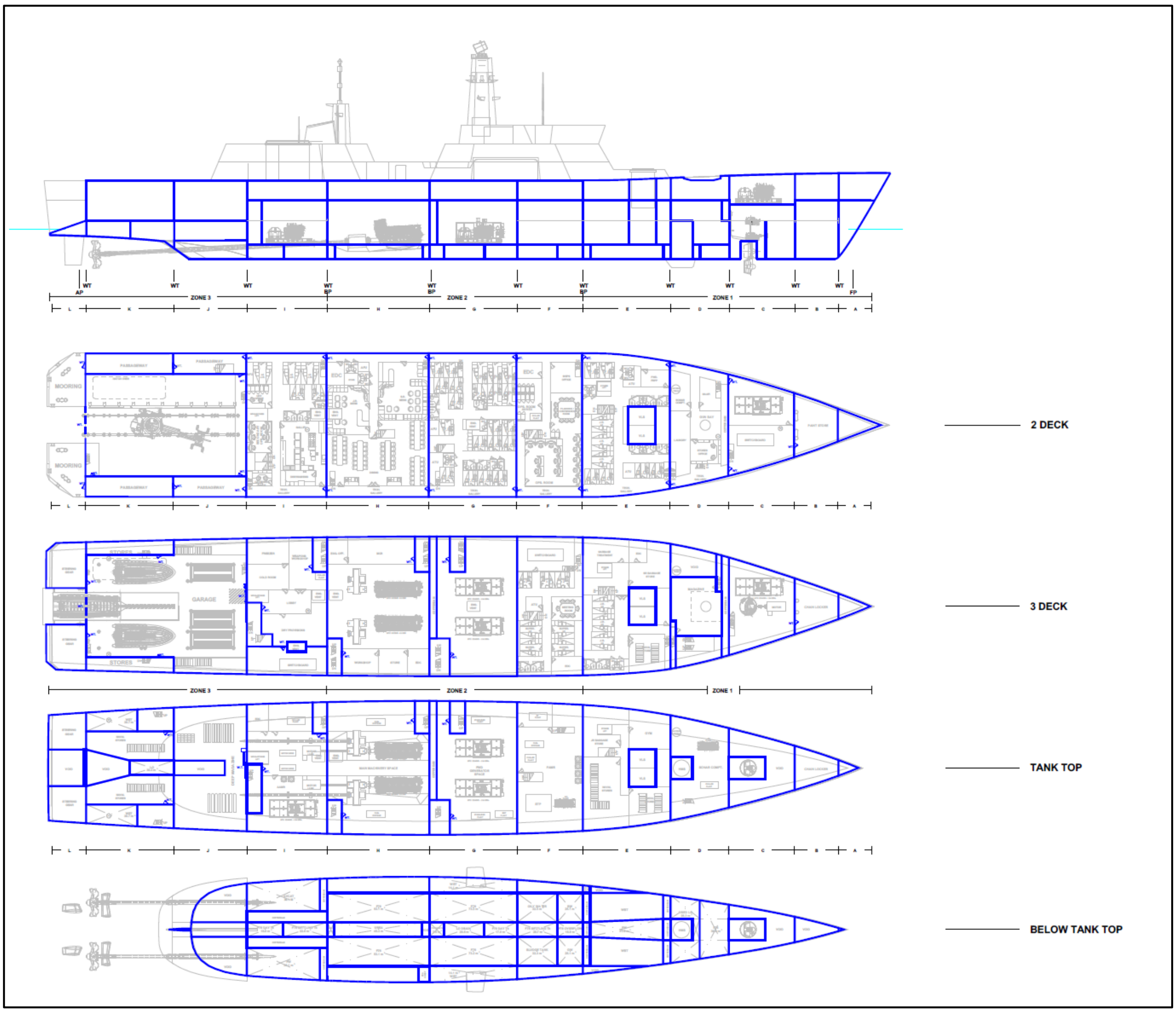


Figure 4: Spartan watertight integrity drawing

3. Integrating hostile vulnerability and the static carpet plot

The Purple Fire tool has been in use for several years to quantify vulnerability to weapon attack (Schofield, J.S. 2018). It can simulate the effects of above and underwater threats on ships and submarines, in terms of damage both to the structure of the vessel and the effect on its systems. This allows a prediction of functional availability after a hostile damage event. Such simulations are typically used to identify and mitigate vulnerabilities during design and as part of in-service operational analysis. For example, the Purple Fire Spartan model is presented in **Figure 5** with its hull, structural definitions, doors and hatches and equipment shown.

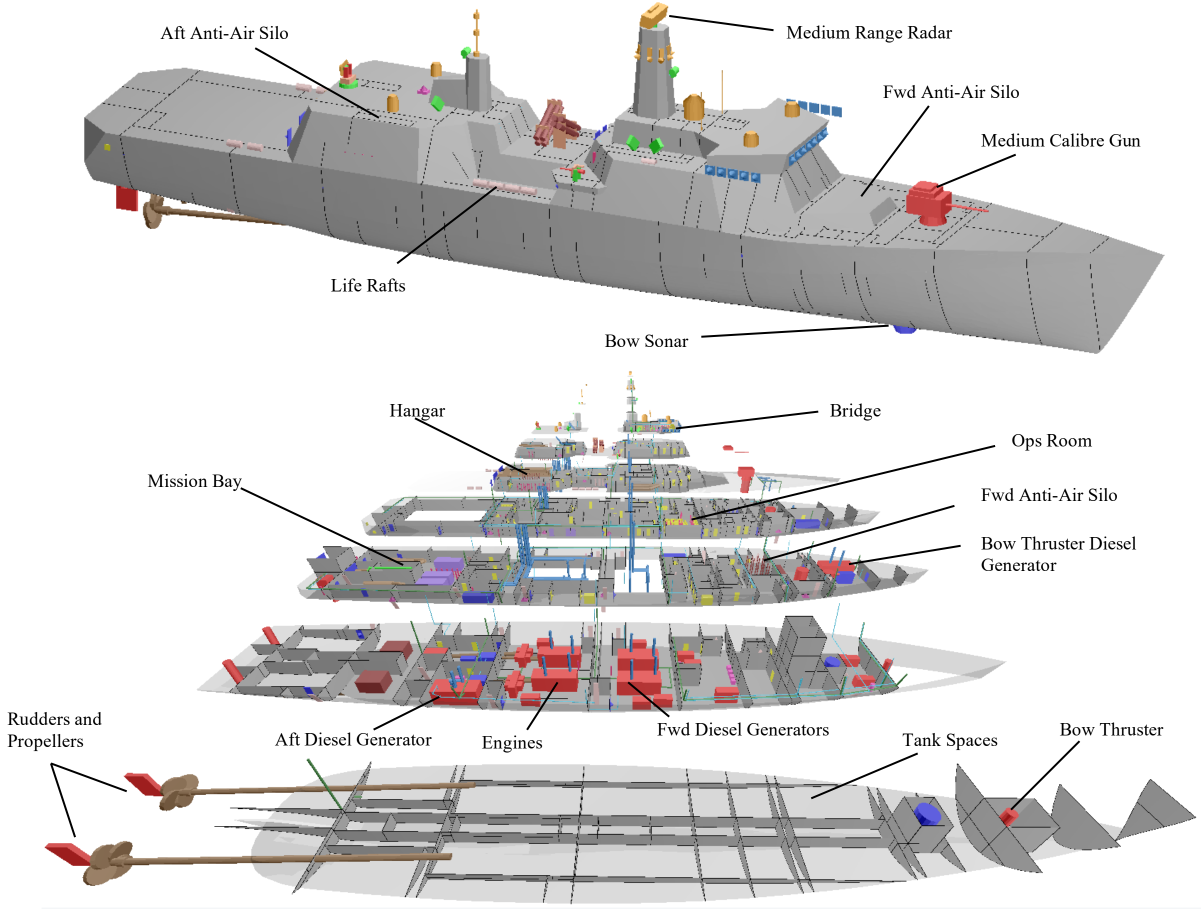


Figure 5: Spartan Purple Fire model external view (top) and split deck internal view (bottom)

Both underwater and above water phenomena are relevant. For underwater events the code predicts structural damage to the underwater hull to establish which zones of the ship are holed. Further internal structural damage is possible as detonation products vent into the vessel, so the flooding may be predicted to spread beyond those zones holed. The same is true for above water weapons, for instance where the blast from a missile ruptures the hull below the waterline, along with damage to internal structure through blast loading or penetration.

Previously the carpet plot was used solely as an input to Purple Fire, in order that the code could judge whether sinking occurs for a given combination of flooded compartments. A carpet plot represents the capacity of a design to resist flooding but is agnostic of the mechanism by which that flooding occurs. Creating these damage extents using hostile threats offers a way of creating large damage cases in a more realistic manner than modelling them using traditional accidental approaches.

The new combined approach allows Purple Fire to provide extra information for the carpet plot, by conducting analysis for the carpet plot cases of poor stability and vessel lost. Primarily this is relevant to the “frontier” cases each of which represent the smallest number of flooded zones extending back from a particular bulkhead that lead to vessel loss or poor stability. There could be a number of scenarios of attack from “design threats” (i.e. those which the ship is designed to withstand and might be present in the Stability and Survivability Book) that could produce the flooding represented by a particular carpet plot case. For example, for a given size of mine there could be a variety of detonation locations which produce the same combination of flooded zones, although with different hole sizes and locations.

For each of these locations the behaviour of the ship in terms of ingress of water, change in attitude, damaged stability and, if needed, time to abandon will be different. Thus, there are in reality a range of outcomes for a given carpet plot case, even if ultimately the state of the ship will be the same. This begs the question, for a given point on the carpet plot, how long will the ship take to sink, or reach poor stability? If abandonment from the sinking ship is needed, how long will it take, how does the change in attitude affect the time and what would be the effect of different sea states?

The most important thing for the carpet plot to present is of course the worst-case outcome from a given flooding extent. However, by integrating the hostile damage prediction with stability (Section 4) and abandonment (Section 5) predictions, these questions can be answered in terms of a range of possible outcomes, providing useful additional information to enhance the carpet plot.

If no hostile event from a relevant threat is found that gives rise to a particular carpet plot case, this is in itself instructive. A multiple-hit simulation can then be used to achieve the given level of damage, and again the carpet plot can be augmenting. Multiple damage cases can now be assessed for a given carpet plot extent and the driving escape times (T_{esc}) and times to sink (T_{sink}) extracted.

4. Integrating vulnerability and ultimate stability time domain simulations

Dynamic seakeeping tools such as FREDYN allow the damaged behaviour of a ship in a seaway to be assessed and enable the visualisation of the flow of water through the internal damaged compartments. The generation of damage cases is traditionally a time-consuming process involving the individual definition of openings between compartments, construction of flooding databases for each compartment under investigation and various other definitions to be defined in numerous input files. The time taken to construct these inputs has previously limited the number and complexity of damage scenarios which can be produced and analysed in a feasible time frame.

In order to create the number of simulations required for a carpet plot calculation a new approach has been developed and is outlined in this section.

4.1. Static initialisation and validation

As per the process diagram seen in **Figure 2**, a Paramarine model is used as the basis for the FREDYN model in line with previous analysis studies. A mesh is created in Paramarine which is passed to FREDYN from which hydrostatic curves are generated and then validated against the Paramarine baseline. FREDYN uses a tank database file at the heart of the flood water calculations. The database gives the mass properties of each compartment to be filled with fluid for each given combination of fill level, heel and trim. This is typically produced within Paramarine and converted to the required format using a MARIN tool. In order to streamline the process and verify that the Purple Fire geometry aligns with the baseline Paramarine geometry, Purple Fire has been coded with the capability to produce tank database files directly. These are compared to the sample files generated using Paramarine as part of the initial validation process. The Purple Fire software is then used to generate one large database encompassing all internal vessel compartments. This is used in all subsequent simulations, negating the need for damage specific database files.

Verification of dynamic simulations can be a complex process and is vital in assuring confidence in the output of seakeeping software. The normal approach for intact and damaged simulations is to validate static criteria such as GZ curves within the time domain software by freezing roll and recording the subsequent settled righting moments. Where the vessel is ultimately lost this approach is no longer possible as no static equilibrium point exists against which the time domain code can be assessed. Instead, an approach is used whereby a reduced damage case is defined, including as many of the full damage cases compartments as possible without causing the vessel to sink, this is created in Paramarine and in Purple Fire, exported to FREDYN and the standard validation approach undertaken. Because of the large number of damage simulations being conducted, this process is not practical for every case, it is therefore proposed that 10% of the damage cases identified as driving cases be fully validated using quasi-static codes as a baseline.

4.2. Internal and external damaged openings

FREDYN's "openings" represent potential flooding between compartments (or from the sea). These can either be pre-existing (e.g. non-watertight structure) or as a result of damage. These have traditionally been manually intensive to define. By giving Purple Fire the ability to output these directly from threat assessments, FREDYN damage scenarios can now be generated automatically in a more time effective manner than achieved previously. The automatic definition minimises errors in user input and ensures alignment between Purple Fire, FREDYN and mEX. The main advantage of the automation though, is the number of openings which can be represented. Whilst typical FREDYN ship representations may ignore much of the non-watertight structure, a simulation generated from Purple Fire can consider all structure and how flood progression is affected.

Purple Fire initially generates the opening shapes required for FREDYN for all hull panels, decks and bulkheads (even watertight structure, in case of damage) but only outputs those needed for a particular scenario. The decision as to which are needed includes a calculation as to which spaces might be exposed to flooding in a given scenario, so that the number of openings used can be minimised to avoid excessive FREDYN runtime. Thus, the openings that are used for a given scenario constitute:

- Damaged hull panels;
- Damaged openings in decks, bulkheads, doors and hatches;
- Hull openings (e.g. mooring points);
- Non-watertight structure, doors and hatches in floodable spaces.

The parameterisation of each opening in FREDYN includes a leak area ratio (the proportion of the area of the opening's polygon through which fluid can flow), a discharge coefficient (representing the efficiency of the flow through the opening) and collapse pressure (above which hydrostatic loading the opening will collapse and have a leak area ratio of unity). In historic assessments a constant discharge coefficient of 0.58 is used and the same is true in Purple Fire's treatment. The leak area ratio is defined depending on structural type and damage. For example, a non-watertight bulkhead can be modelled as an opening with a reduced flow coefficient to represent the likely flow restriction it would represent. Current values for leak area ratio of intact structures are as follows

- Hull panel 0%.
- Watertight plate 0%.
- Openings (e.g. open doorways, vents) 100%.
- Minor structure (e.g. cabin bulkhead) 30%.
- Non-watertight structure (e.g. non-watertight deck) 5%.
- Watertight door/hatch or blast door 0%.
- Non-watertight door/hatch in 10%.
- Minor door 100% (assumes flooding forces door open).

Because damage openings can be defined based on realistic hostile damage caused by mechanisms such as blast, fragmentation and underwater shock, water flow through damaged bulkheads can be defined with realistic areas. In all cases the leak area ratio is augmented by damage. In the case of penetration this can be an additional proportion of the area representing the holing. In the case of full structural rupture this is 100%.

It is recognised that results will be sensitive to these parameters. Work has been conducted previously to understand simulation sensitivity to a number of flooding simulation inputs (Dawson, N.A., 2013), however this did not consider simulations of the scale now being assessed. The scope for future work to explore these sensitivities is explored in section **Error! Reference source not found.**.

The openings defined by Purple Fire for a given scenario can be visualised in both Purple Fire and FREDYN to provide verification. An example against Spartan is shown below. **Figure 6** shows the verification of the external damage openings while **Figure 7** also shows the internal openings. It should be noted that some internal openings correspond to openings in the structure, not linked to damage, for example freeing ports, non-watertight minor structure etc.

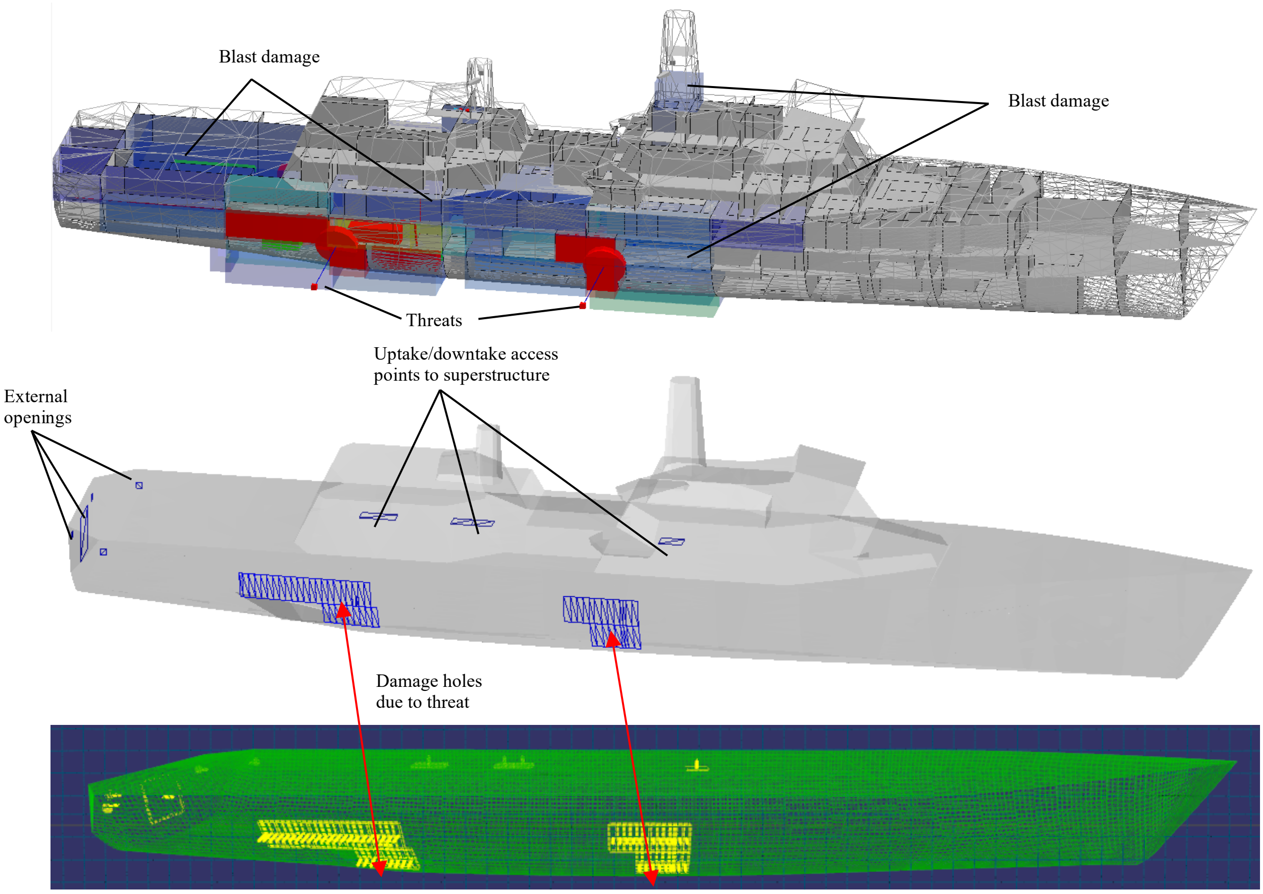


Figure 6: Purple Fire threat damage (top) give openings to the sea (middle) implemented in FREDYN (bottom)

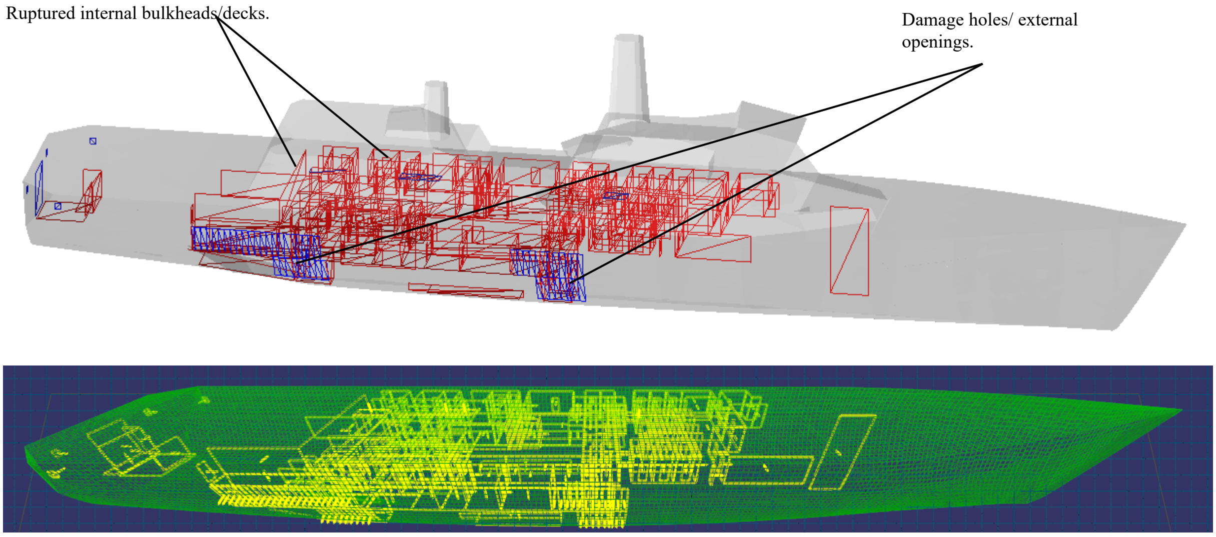


Figure 7: The damage in Purple Fire (top) is automatically exported to FREDYN openings (bottom)

4.3. Environmental inputs

In order to ensure alignment with current static ultimate stability approaches, a max sea state 4 was used for all simulations run under this work. Waves were modelled using a JONSWAP spectrum (Hasselmann et al., 1973) with a peak enhancement factor of 3.3. Simulations were run for an hour or until a capsize condition defined as a 90° heel angle was met. Long crested seas were used in all the simulations. A summary of the wave definition used in the simulations, derived using the World Meteorological Organisation sea state code (Ewing 1974) as guidance, is seen in Table 1:

Table 1: Simulation sea state

Sea State	Modal wave period (s)	Significant wave height (m)
SS4 max	7.35	2.50

Vessel speed was assumed to be zero and waves were defined as beam on to the damage, yaw was fixed to ensure this assumption was maintained. Future work considering different combinations of vessel speed and heading is discussed in section 7.

4.4. Time domain validation strategy

As a result of the complexity of the simulations being run, the number of compartments involved and the number of openings between them, an approach is required to verify that the time domain simulation is behaving in the manner expected and that the results are believable. The authors developed a new toolset to achieve this; for 10% of the runs completed, a visualisation of the flood water progression was created. This visualisation reads the output files of a FREDYN run and allows the floodwater progression through the ship to be visually assessed. In doing so, anomalous openings between compartments can be identified and other non-intuitive behaviours investigated. Whilst the possibility of such errors occurring is low as a result of the automation used to generate them, this also serves as a useful tool to interrogate simulations for features such as trapped buoyancy etc. and could potentially serve as a training aid for ship personnel in the future. An example of the output of this visualiser can be seen in **Figure 8**.

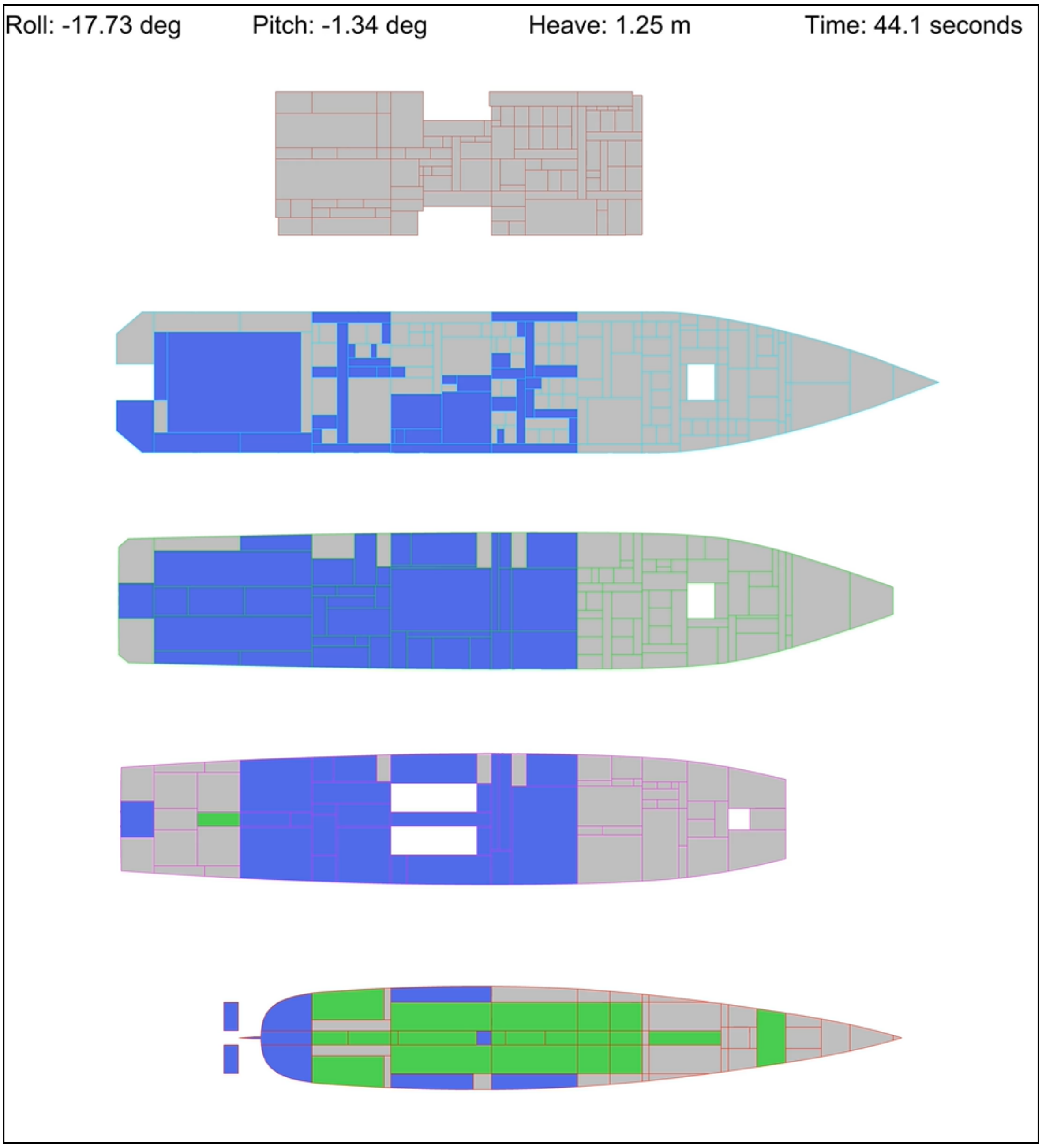


Figure 8: Example of flood water progression verification tool

5. Integrating ultimate stability time domain simulations and escape and evacuation simulations

Purple Fire's link to the maritimeEXODUS (mEX) tool for crew movements has been presented to INEC previously (Schofield, J.S. 2018). mEX is used to give an agent-based simulation of abandonment accounting for probabilistic variations in agent movement and decision making. In short, the link allows the user to automate the creation of battle damaged EXODUS models, simulate a range of probabilistic scenarios to achieve statistically significant results for abandonment and extract timings back into Purple Fire to create metrics, analysis choke points, assess compliance and improve designs.

There are various inputs and phases of initialisation that a user would have to undertake if using mEX directly. These are handled in Purple Fire by setting up a series of inputs which are then passed to mEX which is launched and controlled automatically. Thus, the link from Purple Fire to mEX is similar in philosophy to that to FREDYN already covered.

For example, **Figure 9** shows the automatic generation of the mEX node network (i.e. a network of potential occupiable 0.5m^2 locations for each crew member) with:

- Free space Nodes (green) representing open space;

- Links between nodes determine where the crew can move;
- Boundary Nodes (blue) next to bulkheads/obstacles have slower movement speeds;
- Gaps left around bulky equipment to accurately represent the physical space available
- Door nodes between compartments;
- Deck-to-Deck links via ladder/stair equipment;
- Various escape features modelled including Life Saving Apparatus (LSA), Survival Suits, etc.

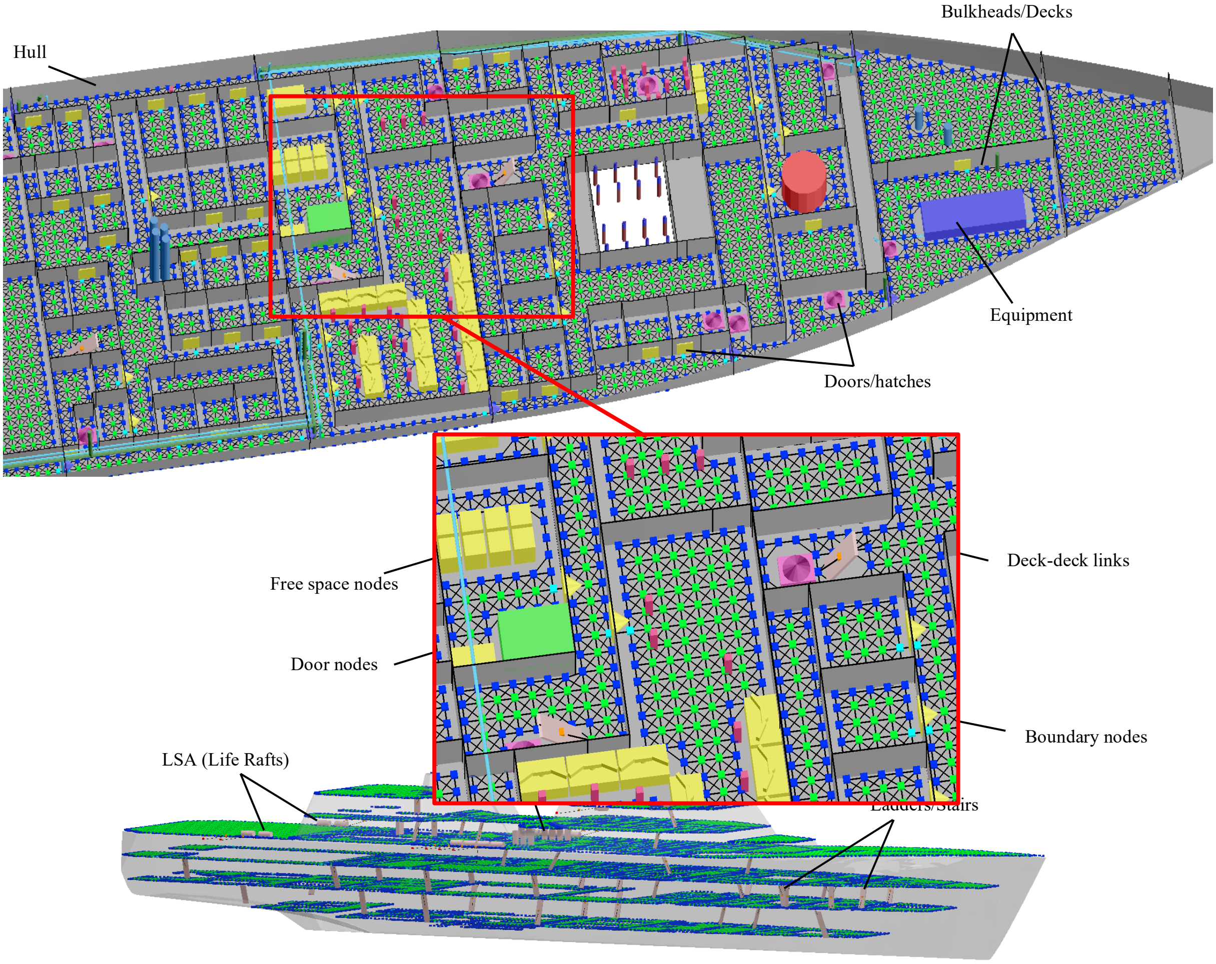


Figure 9: Example of Purple Fire generated mEX network (top) and automatic deck linking (bottom)

Prior to the link to FREDYN it was possible to establish abandonment times with the ship at a fixed attitude accounting for predicted primary damage (such as blocked doorways and impassable spaces). With the availability of FREDYN outputs and more recent work on the mEX link, Purple Fire can now automatically account for:

- Change in vessel attitude: the second by second output of FREDYN is discretised into steps and used as an input to mEX, which contains data for the ability of crew to move around a ship at different angles of heel and trim;
- Motion Induced Interruptions (MIIs) i.e. stumbling due to rapid changes in attitude: these can be interpreted from the attitude results and used to slow the crew movement at a particular time – currently implemented as an additional post evacuation delay calculated from an averaged position (currently assumes 5 second delay per MII);
- Damaged structure: routes are removed from the mEX network if they are deemed to be impassable, because of structural damage or blocked doorways. This extends to ensuring that trapped crew are identified as such and removed from the simulation;
- Injuries to personnel: fatalities are removed from the simulation and the injured are assigned reduced movement speeds;

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6. Example of combined results

For the purposes of this paper, a limited subset of a carpet plot has been studied, varying longitudinal extents and locations in order to capture a range of outcomes. A single threat mechanism of two water borne improvised explosive devices (WBIEDs) has been used. It is notable that two detonations were needed to achieve damage approaching the carpet plot cases. This threat has been applied at multiple locations to achieve the desired longitudinal extents. **Figure 10** highlights the carpet plot points assessed for this example.

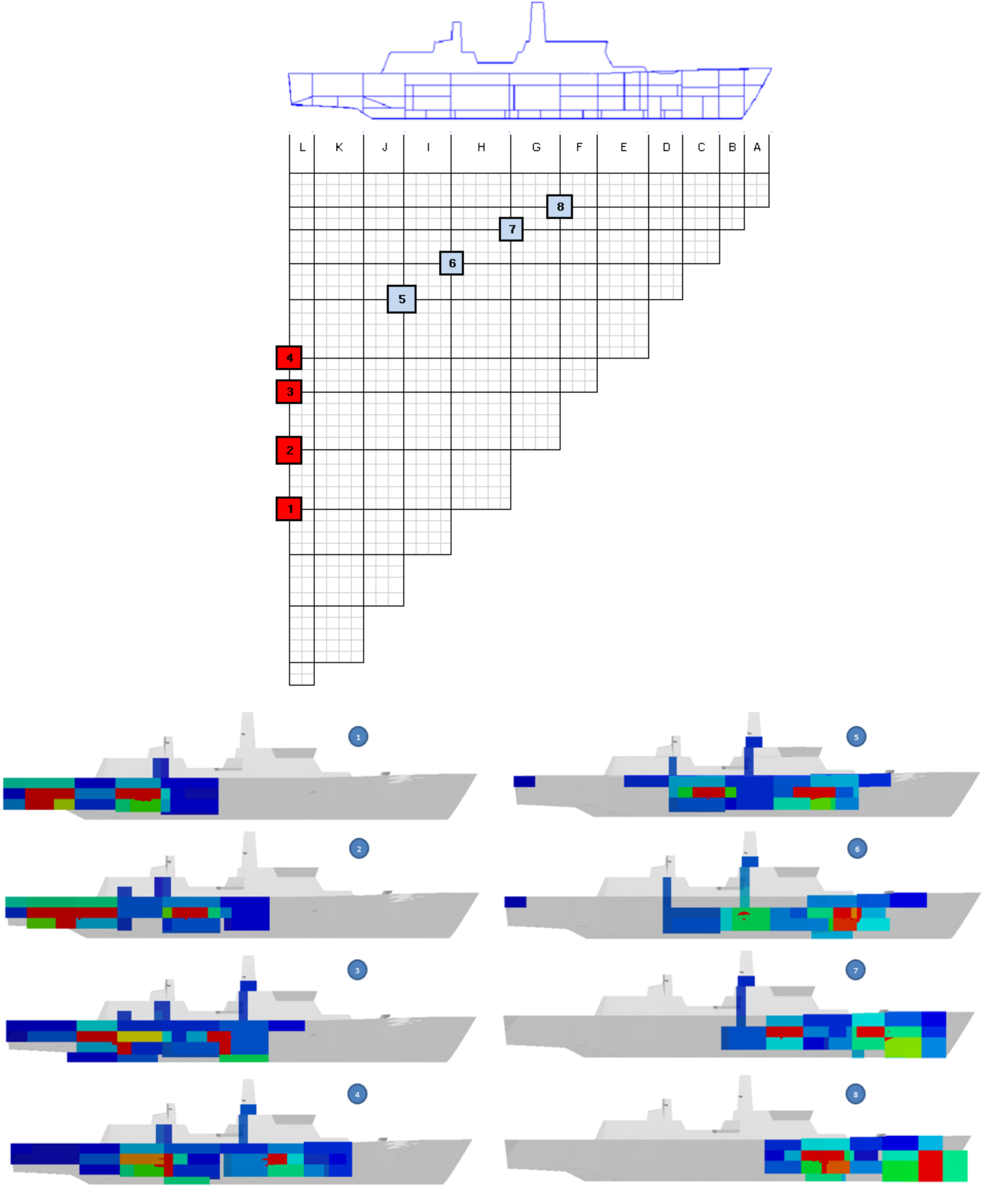

Figure 10: Threat specific carpet plot (2xWBIED)

The resulting cases differ from a traditional accidental carpet plot in that they reflect realistic achievable extents meaning in some cases, compartments within the zone boundaries remain intact, for example in way of double bottom tanks.

Each damage case was generated in Purple Fire based on the threat definition, run in FREDYN, run through mEX and the resulting sinking and escape times compared. **Table 2** outlines the results of the example analysis conducted.

Table 2: Carpet plot results

Run ID	Potential Zone Flooding	Sink Time [min]	Mean Evac Time [min]	Min Evac Time [min]	Max Evac Time [min]
1	L-H	8.0	5.0	3.7	14.9
2	L-G	1.8	5.1	3.7	15.7
3	L-F	11.8	5.3	4.0	16.3
4	L-E	23.3	5.1	4.0	10.9
5	I-D[2]	N/A	5.3	4.0	15.1
6	H-C[3]	N/A	4.9	3.8	10.2
7	G-B	N/A	5.0	3.9	15.3
8	F-A	N/A	5.1	3.7	15.4

1 – The boundaries between H and G remain intact so flood water cannot flow between.
2. – The blast reaches into zone I by breaching a WT door in the technical gallery on the WT deck.
3. – The blast reaches into zone C by breaching a WT door on the WT deck.

The key points from this subset of cases are that:

- In all cases the average expected evacuation times are significantly shorter than the deterministic requirement of 30 minutes;
- In the sinking cases, the ship sank faster than the 30 minute criteria despite this platform being of a demonstrably survivable design;
- In the majority of the sinking cases, the average evacuation time is less than the predicted sink time implying the possibility that recoverability actions could be sensibly undertaken;

7. Conclusions

A new combined approach to the analysis of ultimate stability, vulnerability and escape and evacuation is proposed, combining dynamic time domain analysis of both damaged vessel motions and escape and evacuation with a central vulnerability assessment. The approach replaces deterministic escape time requirement criteria with actual times to sink and assesses carpet plot cases in the time domain in a seaway, allowing vessel motions to be understood and integrated into escape and evacuation modelling.

The work presented in this paper represents an initial phase to streamline the workflow and develop the tools needed to run analysis of this type. Further work is now required to understand the sensitivity of the analysis to the key inputs, to improve the interface with mEX and to further explore how the approach can be integrated into naval vessel safety certification. Of particular interest:

- Exploration of a more probabilistic method of determining sink and escape times based on a probability density of results for each carpet plot extent.
- Sensitivity studies of discharge and leak coefficients for types of opening, to be followed up by physical or analytical testing of key characteristics.
- Consideration of collapse pressures for non-watertight bulkheads of typical construction. Achieved through literature study, FE analysis or physical testing.
- Exploration of ways in which escape and evacuation can be better integrated into vulnerability assessments and how this can be certified.
- Consideration of whether data of the kind generated is beneficial to the operator or whether it is better suited for certification purposes only.
- Sensitivity study to examine the impact of varying vessel speed, wave direction, wave type and other environmental conditions on final result. Continued work to assess best practice for future analysis.
- Implementation of the modelling of deck motions using the mEX hazard module to slow down personnel based on their location and the vessel motions thus accounting for MII events. The process has been setup to allow this interaction to be modelled, final implementation is now required in the next phase of work.
- Literature study and/or experimentation in facilities such as the Damage Repair Instructional Unit (DRUI) to establish typical delays in naval evacuee motions following an MII induced stumble event and general deck motions.

- Implementation of mEX route denial as a result of flood water progression. The process has been setup to allow this interaction to be modelled, final implementation is now required in the next phase of work.
- Consideration of realistic reductions in naval personnel movements as a function of water depth and the point at which a compartment should be considered impassable. Derived from a literature study, analytical modelling or from experimental results from a facility such as the DRUI.
- Consideration of limiting the use of escape mechanisms according to their heel limit. Implementation of criteria to allow jumping into the water once deck edge is below Defence Standard 02-148 limits.

A naval combatant has been used as the example in the work presented in this study, but the use of the approach on commercial vessels has also been considered by the authors. Test cases of large commercial passenger vessels have shown that the same analysis can be conducted with minimal need for alteration of the approach. Threats aligning with more accidental mechanisms such as collision can be implemented within the vulnerability software to allow their inclusion. It is the authors' opinion that the inclusion of realistic vessel motions and flooding in escape and evacuation assessments of both naval and commercial vessels is essential to capture their effect on escape times. In implementing the proposed approach, the authors have developed a toolset which allows analysis to be conducted at a greater individual scale than previously achieved and across a wider number of cases than previously possible. These developments mean that analysis of an entire carpet plot worth of cases is now possible where using previous techniques this would have been both technically and commercially unviable.

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