SURVIVE: WARSHIP SURVIVABILITY ASSESSMENT FROM CONCEPT TO SERVICE

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INTRODUCTION

(By David Manley, Head of Vulnerability Reduction and Shock Engineering, Directorate of Sea Systems)

The survivability of RN and RFA surface ships is currently undergoing something of a renaissance. RN vessels have for many years enjoyed highly effective shock protection, and signature control has, to some extent, also been a feature of past designs. Operation Corporate exposed a number of significant shortcomings, many in the area of surface ship vulnerability. The Type 23 frigate embodied a number of lessons learnt from the Falklands conflict, but it was not until the design of the Type 45 destroyer that effective above and underwater vulnerability requirements were introduced. Over the last few years DEC(AWE) and its supporters in DE&S and DSTL have been developing the Survivability Strategy which introduces baseline requirements and mandated design features to improve ship survivability. To a great extent the ability to specify effective requirements for vulnerability has stemmed from the development of the SURVIVE vulnerability assessment code and its concept level sibling, "SURVIVE Lite" (both of which are now being exported to a selection of NATO and allied nations). The Maritime Strategic Capabilities Agreement now mandates the use of SURVIVE for surface ship vulnerability and lethality assessment; this article aims to describe the code and its applicability to surface ships (and submarines), an applicability that now extends beyond pure vulnerability assessment to cover structural strength, stability, explosive safety and escape and evacuation.

SETTING THE SCENE

Survivability is defined as the ability of a vessel to complete a mission successfully in a hostile environment. It can be broken down into three main areas: susceptibility (the chance of being hit), vulnerability (the chance of loss of mission capability given a hit) and recoverability (the chance of restoring mission capability through reconfiguration or repair). It is possible for a warship to be designed to withstand repeated attacks through a combination of avoiding hits, avoiding damage and the ability to recover capability.

The approach to survivability management of modern warship procurement is complex, but good levels of survivability can be achieved without excessive cost implications, provided survivability is considered from the very early stages of the design. The initial layout of primary spaces on board can have a big knock-on effect on final capability. Separated machinery spaces, topside layout that allows separation of sensor and communications assets, protection of critical spaces through location at the least susceptible and least vulnerable points, provision of reversionary options for critical spaces and magazines surrounded by non-critical compartment all constitute good survivability features. This means that even the very first concepts can be assessed for survivability. Through an iterative process the effect of design options can be established and the best features identified and incorporated, often at little or even zero cost. The most effective modifications are often as simple as the re-routing of a cable or pipe, the separation of redundant items or the concentration of critical items.

Consideration of survivability does not stop when a vessel is commissioned. Refit, the embarkation of new weapons, change of role or change of threats all affect how a vessel might be affected by an attack. This can be assessed very cheaply, if an existing model of the platform exists from its design stage, since it is likely that only minor modifications will be needed to represent the altered vessel, and only certain areas will be of interest where the level of survivability might have changed or be in doubt.

Targets on survivability written early on form a platform on which to base the management process, and can be readily defined to give a transparent requirement along with logical and achievable goals to follow to ensure good performance. In this way survivability management becomes an integral feature of the design, meaning that it is not seen as an afterthought adding cost and complexity.

SURVIVE ™

SURVIVE has been under development for over a decade, having originally come about from the combination of several different UK vulnerability codes. The basic stages of the SURVIVE process is shown below. Primary and secondary damage to a ship or submarine target are predicted in a given scenario. SURVIVE works in enough detail to adequately predict the interaction whilst still being fast running. The reaction of the ship's systems and crew are simulated and the simulation progresses through time as appropriate, with further incoming threats possible depending on the scenario. Numerical and visual results are outputted in user-friendly forms.

SURVIVE has been developed specifically for the assessment of warships, but is just as applicable to civil shipping, which is increasingly experiencing the terrorist threat, and must adhere to regulations covering fire, flooding, escape and evacuation.

Each of the aspects of the SURVIVE process will now be discussed in turn.

Input: Ship Target

SURVIVE offers a versatile target definition capability, as illustrated by the following examples.

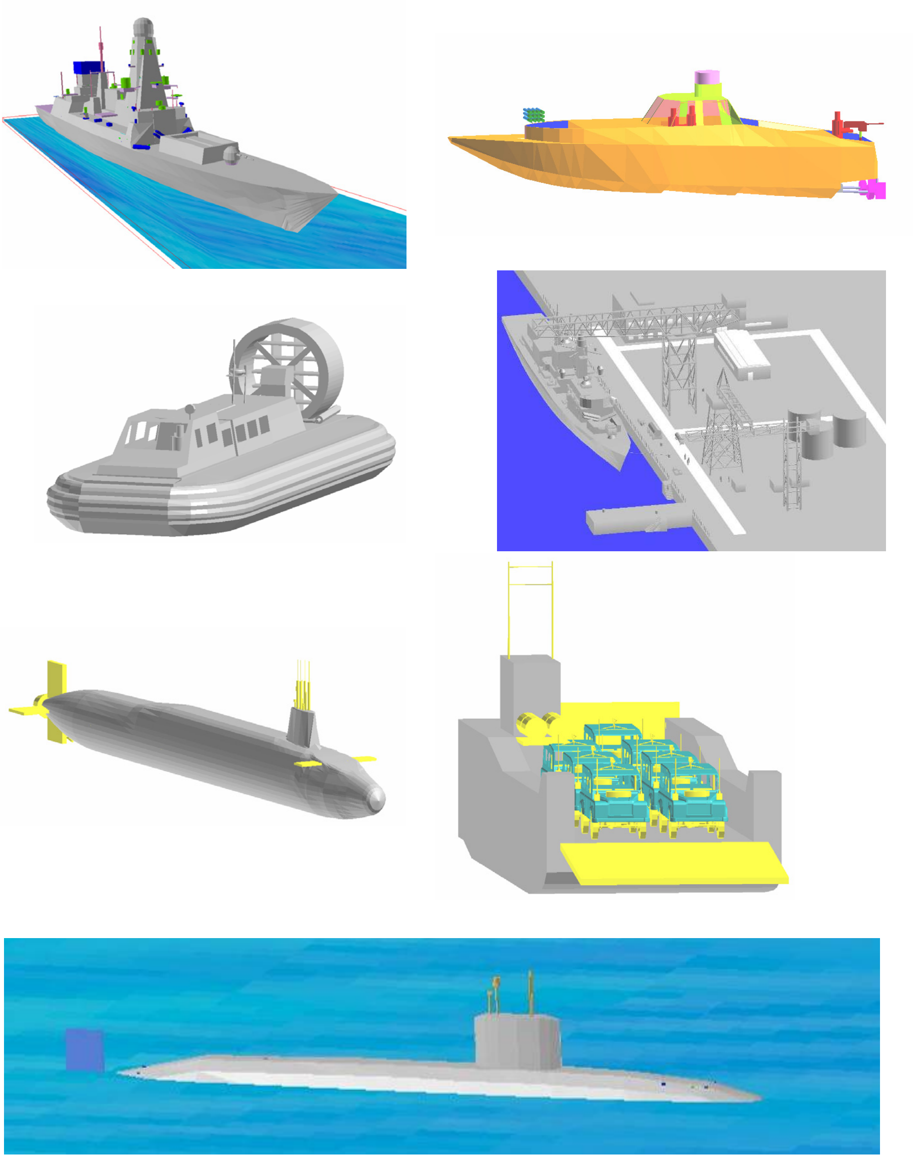


FIG.1 - VERSATILITY OF SURVIVE NAVAL TARGETS

The SURVIVE target description starts with a triangulated outer skin surrounding internal structure made up of cuboid shaped building blocks. These simple blocks are joined together to create the complex compartmentalisation seen in modern warships.

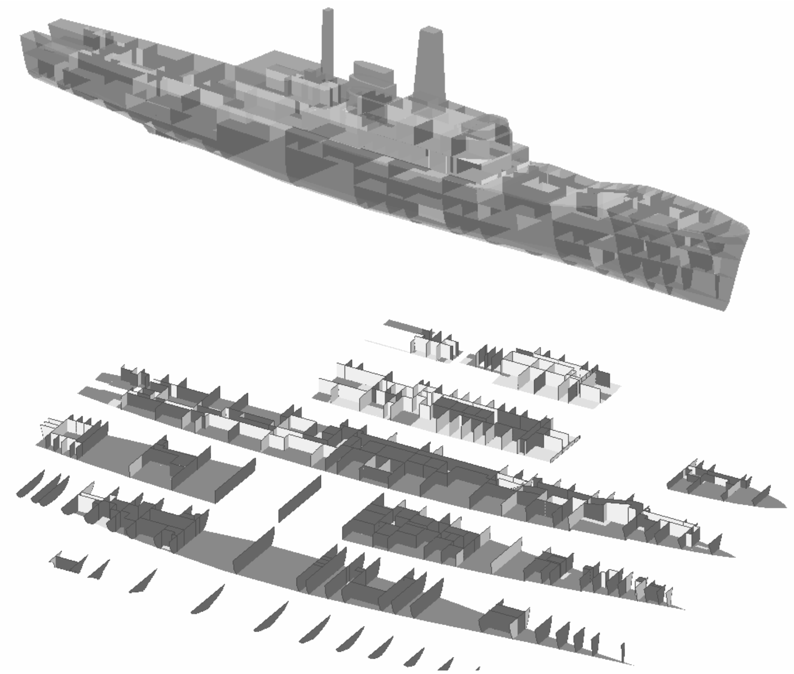


FIG.2 - SURVIVE COMPARTMENTALISATION EXAMPLE

Boundaries making up the outer skin and internal structure are assigned properties covering material, thickness, edge connection (e.g. welding type), stiffening, thermal insulation and permeability to flooding and smoke transfer. Doors and hatches are represented as openings in internal or external structure with properties covering material, thickness, blast resistance and times associated with opening and closing.

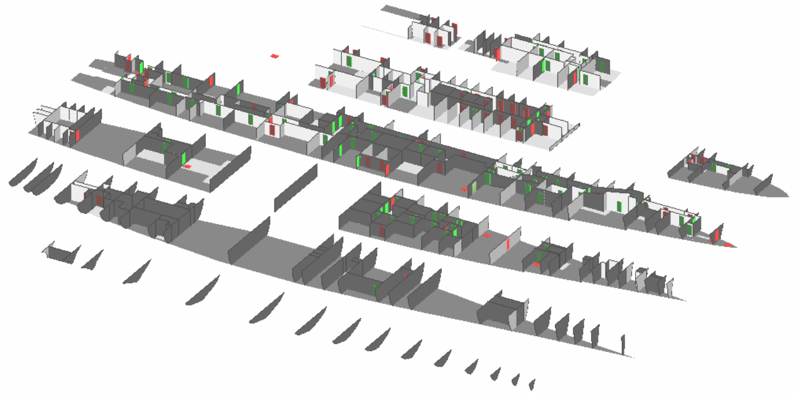


FIG.3 - SURVIVE DOOR AND HATCH EXAMPLE

Items of equipment (including crew) are represented as a series of simple shapes, or can be built up in any user-specified shape if required. Each equipment has associated mounting characteristics and is allocated to a category and sub-category to allow SURVIVE to look up failure criteria for the item's response to each damage mechanism, along with repair or replacement times (and spares requirements) if appropriate.

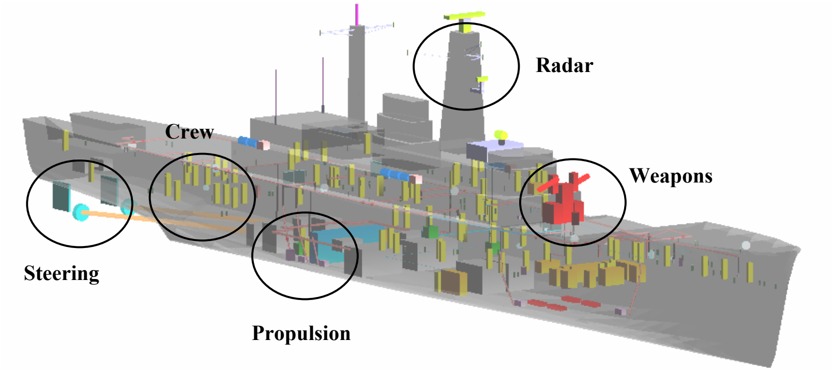
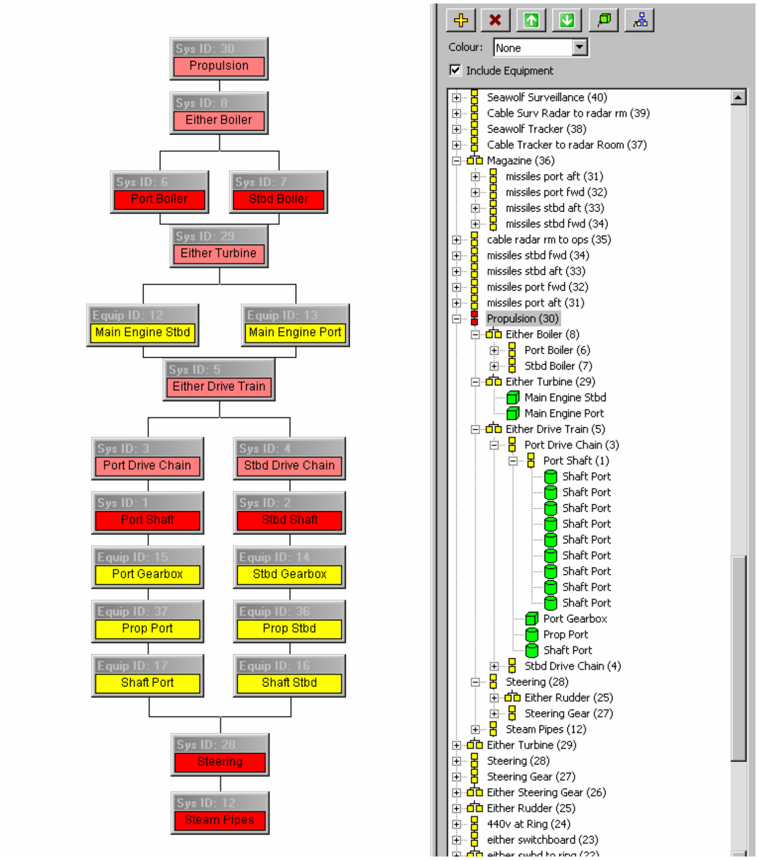


FIG.4 - SURVIVE EQUIPMENT AND CREW EXAMPLE

Equipment items are built up into logical systems representing the functionality of the ship. The resulting fault trees give a clear visual impression of what must be available for the ship to conduct a particular function, such as propulsion, naval gunfire support or the operation of embarked aircraft.



Colour: None

☑ Include Equipment

FIG.5 - SURVIVE SYSTEM BUILDER EXAMPLE

Very complex items, such as embarked aircraft and land vehicles, can be represented in detail through the embedding of one SURVIVE target description inside another, if the particular study requires this level of detail. The SURVIVE Controller manages the assessment of damage to each embarked asset and the host vessel in separate instances of SURVIVE and controls the transfer of data between them. In this way many iterations of damage can occur with munition reactions on the host or embarked assets communicating. More on sympathetic detonations later.

In addition to its role in the assessment of embarked assets, the SURVIVE Controller represents a methodology for the linking of SURVIVE to other simulation codes, for example battle or taskforce level simulations. It uses TCP/IP messaging to communicate with any applications under its control, offering easy expansion to communication with other codes. For example, a battle level code might request information on the attack of a particular vessel by a given threat at a certain instance in time, and the SURVIVE Controller could report back the status of the ship and its systems immediately after the attack and subsequently at each time step thereafter.

Input: Weapon

One or more threat weapons can be defined in a given scenario. The main properties of each threat that can be included are:

- Geometry (mass, length, diameter, nose angle);
- Fuzing (trigger properties, fuze time/standoff);
- Charge (explosive type, mass, warhead position);
- Fuel (mass and type, for contribution to fire loading);
- Shaped charge jet (JETPEN input, see later);
- Fragmentation types (mass, material, shape & velocity for each type);
- Fragmentation distribution (fragmentation types applied to angular bands around the weapon axis).

Input: Scenario/Susceptibility

As part of the scenario the user can choose which of the SURVIVE algorithms are to be included (more later) along with the extent required for time-based mechanisms.

The number of attacks to be simulated and their locations can take a variety of forms. The most simple is a uniform distribution of points covering the full extent of the ship, for example a 2-dimensional grid of points for an above water sea skimming weapon or a 3-dimensional grid of underwater detonation locations. The points making up the grid can also be randomised for a more statistical approach. Attack grids are useful during the assessment of new ship designs to ensure that all vulnerable areas are identified, but they do not always represent the distributions to be expected for real world threats. To more accurately quantify the effect of these, it is necessary to introduce the susceptibility of the target to the specific threat. To achieve this SURVIVE is linked to all the major UK naval susceptibility codes, namely SPECTRE for radar cross section, SIREX for infrared susceptibility, ODIN for torpedo detonation points and TMSS for mine activation locations.

For each of the attacks defined by the scenario, SURVIVE predicts the path taken by the weapon as it moves towards and through the ship, and whether and where detonation will occur.

A zero velocity weapon (e.g. mine) will detonate at the point specified. If a weapon is powered (e.g. missile or torpedo) then it will proceed along the vector dictated by the scenario (unless ricochet is predicted), with its fuze characteristics deciding the detonation location. An un-powered weapon (e.g. bullet, shell) will experience gravity and fluid drag (be it in air or water) in addition to the other predictions.

At each interaction of the threat with a piece of structure or an equipment item SURVIVE predicts, depending on the threat and properties of the structure, whether penetration occurs, what size of hole is made, whether ricochet occurs, and the residual properties of the threat. A ricocheting threat may or may not continue along its new path, depending on the options selected by the user.

Primary Damage Prediction: Blast (Internal and External)

SURVIVE contains a number of algorithms for predicting the level of blast applied by an explosive charge and the propagation of that blast internally or externally. The simplest of these methods considers the short-timescale impulse loading applied to local structure along with the longer time quasi-static pressure that can cause damage to structure further from the detonation compartment. The spread of blast through doors, hatches, windows and patches, all of which may be weaker than the surrounding structure, is an important factor in correctly establishing the effect of blast.

More complex equations can be used in certain cases to predict blast levels where the chemical composition of the explosive is important, or where detonation or blast venting occurs in large spaces such as hangars, machinery spaces or large accommodation compartments. In these instances the ‘traditional’ methods of blast prediction break down and do not agree well with trials data.

The visualisation of blast can be coloured by severity, as shown below. Numerical levels of blast pressure experienced can also be interrogated.

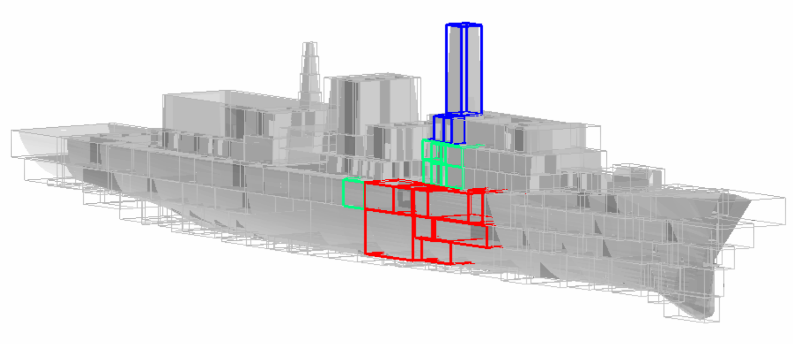


FIG.6 - VISUALISATION OF BLAST SPREAD

Primary Damage Prediction: Fragmentation Tracing and Penetration

SURVIVE generates many thousands of test lines orientated around the threat’s primary axis to represent possible initial paths for any fragmentation. The required fragmentation distribution is allocated to these test lines probabilistically before SURVIVE begins to trace the lines away from the detonation point. Each time a line interacts with structure or equipment SURVIVE tests for penetration, ricochet, and also equipment damage where appropriate. Where some or all of the fragments on a particular line are predicted to ricochet, the new direction is represented by a new test line and the iteration continues.

SURVIVE contains a number of different penetration rules that are used depending on the fragment/target properties for each individual interaction. These include DRI, JTCG, KEPEN, Heatherington, Lambert, Lord, NCRE, SRI and Thor. In addition QinetiQ's JETPEN code is used to handle shaped charge jet penetration.

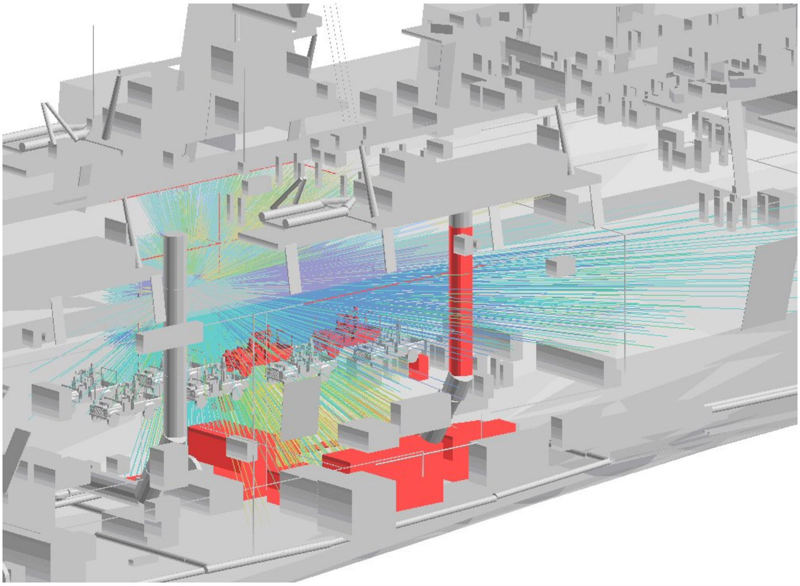


FIG.7 - VISUALISATION OF FRAGMENTATION SPREAD

Depending on the user settings selected, SURVIVE can apply gravity, drag or ricochet, and also undertake an analysis of fragment energies projected beyond the ship for harbour safety case assessment.

Primary Damage Prediction: Underwater Shock (Holing and Equipment Damage)

Underwater detonations cause waterborne shock waves that can damage both structure and installed equipment. SURVIVE caters for both outcomes, using a number of rules to calculation shock holing size to outer and inner hulls and the Shock Grade Curve method to measure effect of shock inside the ship. The grade curves predict the shock induced motion of a particular piece of structure. In addition to the 'standard' grade curves SURVIVE can accept data for numerically derived grade curves that represent a particular platform. Hard mounted equipment experience the full effect of this motion, whilst un-mounted items can be thrown through the air and collide with structure or other equipment. Where shock mounts are installed to protect items SURVIVE carries out an assessment of mount oscillation to establish the above-mount loading seen and whether mount bottoming occurs. For rafted items a coupled system of equipment mounted on a raft that is itself mounted can be utilised.

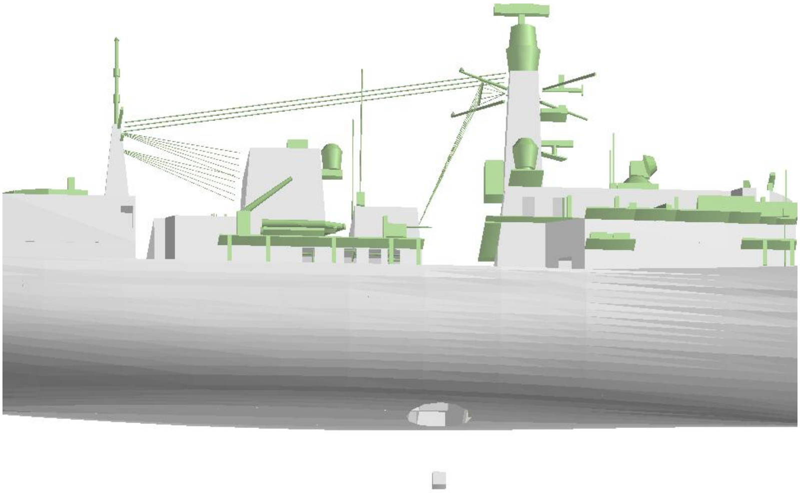


FIG.8 - VISUALISATION OF UNDERWATER SHOCK HOLING

Primary Damage Prediction: Whipping

SURVIVE uses a spring-beam representation of the longitudinal structure of a ship or submarine to assess the effect of an oscillating underwater bubble of explosive products. This predicts what modes the platform is excited in and the maximum bending imposed at each point along the structure. This whipping factor is compared to known data for different types of vessel to establish whether permanent deformation or even total loss of longitudinal strength occurs. The SURVIVE output below shows the severity of the whipping motion imparted from shots under the centreline.

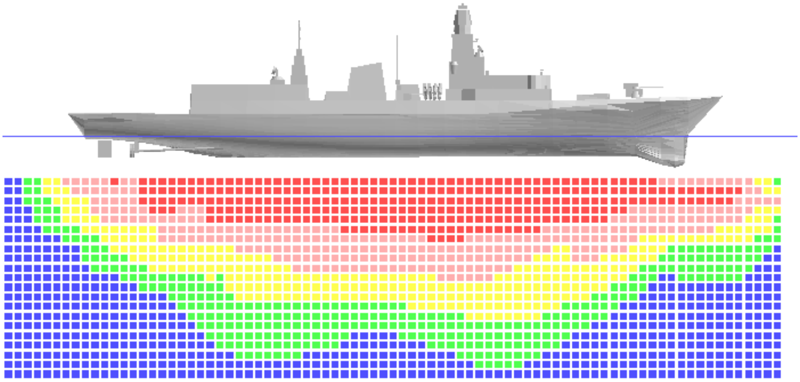


FIG.9 - EXAMPLE SURVIVE WHIPPING CONTOURS FOR SHOTS UNDER THE CENTRELINE

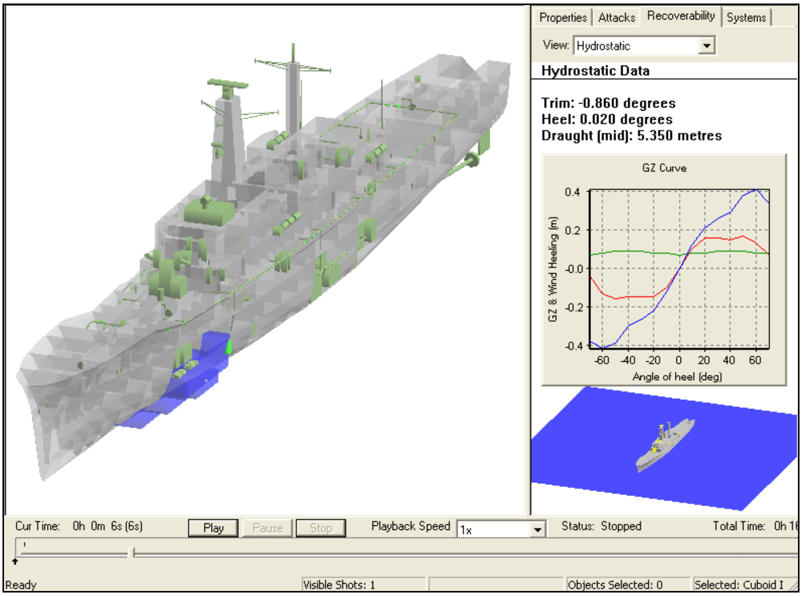
Primary Damage Prediction: Bubble Effects

Further underwater effects can be produced by the explosive bubble, namely jetting and pluming. Bubble jetting occurs when the oscillating bubble collapses onto the hull, in the process producing a high velocity jet of water that can penetrate the ship right from keel to superstructure. A water plume can be produced when a bubble reaches the surface rather than impacting the hull, and can be significant to light craft, such as hovercraft.

Secondary Damage Prediction: Flooding and Stability

Flood water can propagate through external and internal structure damaged by the primary mechanisms, and also through intact non-watertight structure. At each time step SURVIVE calculates the flooded state of each compartment and finds the new static attitude accounting for the floodwater. As will be discussed later, automatic and manual fire fighting and pumping occurring during the recoverability phase are included in the flooding predicted.

At specified intervals a static stability check is also undertaken, accounting for the free surface effect and applied wind heeling lever. All flooding and stability information can be seen in the SURVIVE output below. Note that SURVIVE takes full account of the shape of the hull, although the visual output is more box-like.



View: Hydrostatic

Hydrostatic Data

Trim: -0.860 degrees
Heel: 0.020 degrees
Draught (mid): 5.350 metres

Cur Time: 0h 0m 6s (6s)
Playback Speed 1x
Status: Stopped
Total Time: 0h 1

Ready
Visible Shots: 1
Objects Selected: 0
Selected: Cuboid I

FIG.10 - SURVIVE VISUALISATION OF FLOODING EXTENT, NEW ATTITUDE AND STABILITY
(INTACT/DAMAGED RIGHTING LEVER AND WIND HEELING LEVER)

Secondary Damage Prediction: Ultimate Strength & Wave Bending

The structural representation of the ship in SURVIVE includes information on the type and spacing of stiffeners at any location, which can be built up very quickly in an easy-to-user interface.

By combining this with rules dictating the effect of deck-bulkhead joints and hull shape SURVIVE can calculate the ultimate strength of the ship at any longitudinal location in the intact and damaged states. This is compared to the wave induced bending moment, accounting for any flooding present, in the sea state scenario to establish when loss of strength occurs.

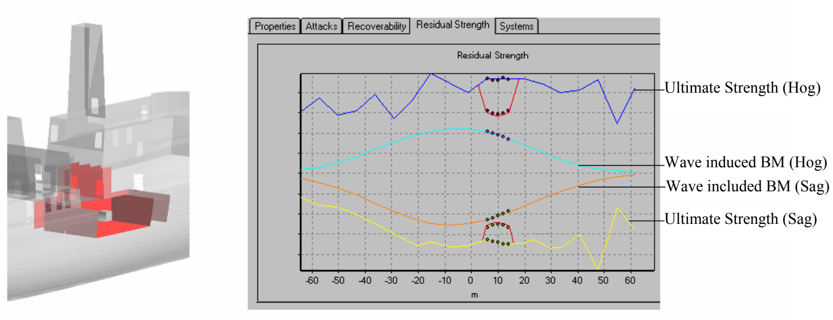


FIG.11 - SURVIVE VISUALISATION OF DAMAGED ULTIMATE STRENGTH AND APPLIED BENDING MOMENT

Secondary Damage Prediction: Fire & Smoke

SURVIVE uses a two-zone fire model to predict the spread of fire and smoke through the ship and to the external environment. It tracks boundary temperature on both sides, conduction through the boundaries and allows different insulation schemes to be applied. Fire loads are applied automatically depending on compartment function, data having come from a survey of a Type 23 frigate. Custom fire loads can also be defined for special cases.

Compartments that receive sufficient incident heat either via their boundaries or hot smoke can catch fire. In common with the other algorithms run times are short; a 2 hour fire scenario on a typical warship takes less than 30 seconds to process thus allowing a wide variety of scenarios to be tested. The model responds dynamically to changes in the scenario (such as doors being opened and closed) and considers the effects of manual or automatic fire fighting, which will be discussed later.

Secondary Damage Prediction: Magazine Detonation

As SURVIVE simulates the spread of damage through the ship, it tracks the effect of primary and secondary mechanisms on stowed munitions. By comparing cumulative damage against initiation criteria specific to the munition involved, it can predict when a reaction occurs and the order of the reaction from a simple burn to a full detonation. The primary and secondary damage due to this new event is then simulated along with the initial damage to give an overall effect.

Reaction to Damage: Equipment and System Vulnerability

The effect of each damage mechanism on each item of equipment is predicted, with a set of kill criteria specific to each category/subcategory combination giving the probability that a given item is damaged irreparably, damaged but repairable, or degraded. This probabilistic approach feeds the overall probability of immediate equipment loss, i.e. the vulnerability to the particular attack. The equipment vulnerabilities are combined to give the vulnerability of each system using a Monte Carlo analysis of the system fault trees. In addition a deterministic equipment status and system is allocated to allow the recoverability assessment to proceed.

Reaction to Damage: Crew Movements, Escape and Evacuation

Crew movements are simulated on a network of paths making up routes within and between compartments and around the external walkways of the ship as shown below.

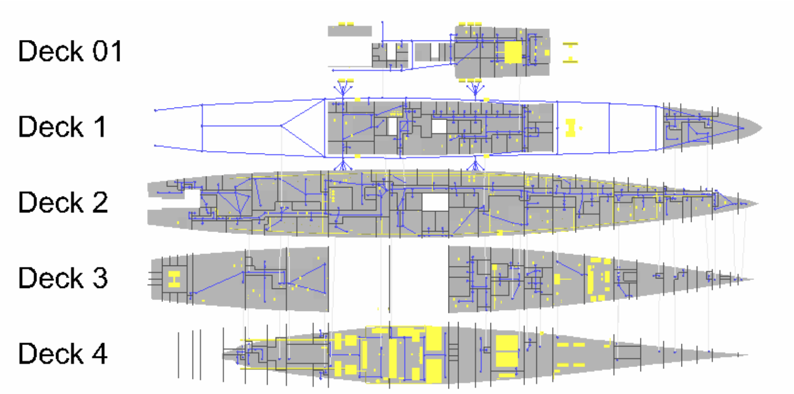


FIG.12 - PATHS MAKING UP A SURVIVE CREW MOVEMENT NETWORK

The speed that a particular crewmember can take along a particular path depends on factors such as congestion, ship's attitude, equipment being carried, availability of lighting, compartment type and presence of smoke. When a path runs through a door or hatch opening and closing times are important. A queue may form at one or both sides of the opening and the last crewmember through must close the door or hatch if the watertight condition of the ship so dictates. Damage to compartments may render paths difficult or impossible to pass, whilst doors or hatches may be blown open or jammed shut, making movement either easier or impossible.

Each crewmember continuously re-evaluates the optimum route to achieve his particular aim, just as a trained crewmember would. Thus crew automatically react to changes in ship condition, such as the spread of fire or onset of new damage following a new attack.

The uses of the crew movement capability are twofold. Firstly the feature is needed for the simulation of recoverability - in undertaking damage searches, changing between ship states or diagnosing and recovering from fires, floods and damaged capability. Secondly crew evacuation simulations are possible, either when abandonment is deemed necessary by the recoverability simulation or as part of the assessment of the safety of the platform. Options for ship layouts and crew distributions can be explored to optimise escape and evacuation times.

Reaction to Damage: Command Decisions

Part of the scenario defined for a recoverability simulation is the command aim that must be maintained. This is represented by one of the ship's functional systems at any specific time. For example, the command aim might be to undertake air operations for two hours, followed by the need to maintain full propulsion for a further two hours. Both air operations and full propulsion can be represented as a SURVIVE system.

At each time step SURVIVE works out a strategy to maintain the command aim, encompassing the undertaking of damage control and fire fighting activities, the reconfiguration of distribution systems and the repair or replacement of damaged equipment. These activities are all dependent on the management of the available crew and resources. Where the situation is irrecoverable through excessive damage or lack of resources SURVIVE will be unable to construct an effective restoration policy, and will thus order abandonment of the ship.

Reaction to Damage: Damage Control and Fire Fighting

SURVIVE issues instructions to available crewmembers to carry out fire fighting, boundary cooling, smoke removal, containment, pumping, leak stopping and shoring operations. Methods are consistent with current Royal Navy methods, but with flexibility to investigate the benefits of altered doctrine or new technologies. Tasks are undertaken based on availability of suitably skilled crew and necessary materials or services.

Reaction to Damage: Reconfiguration, Repair and Replacement

As part of maintenance of the command aim either automatic or manual reconfigurations of the ship's distribution systems are undertaken by SURVIVE through the use of network flow algorithms. This might occur in order to isolate a leaking water pipe, reconfigure a damaged electrical system or provide supply to an equipment that must be turned on to carry out damage control or maintain the command aim.

Items of equipment rendered damaged are repaired or replaced on priority basis given command aim and the availability of the required crew skills and necessary materials or spares.

Repetition at Many Threat Locations

Efficient coding and an appropriate level of detail in target description and damage assessment algorithms mean that many analysis points can be considered in a short space of time. A typical simulation time for a single threat exhibiting the main primary above water damage mechanisms is a handful of seconds, making very large numbers of repetitions commonplace. Underwater detonations require less processing and are even more rapid. The number of attack points chosen can be determined via a sensitivity analysis of point separation, but often extends to several hundreds of thousands of analyses.

Numerical results are averaged for each item of equipment or functional system to give an overall probability of escaping damage. The binary nature of system availability through time (a system is either available or not, although degraded capabilities can be included as separate systems) becomes probabilistic with the chance of availability at a given instance post-hit being available. This leads to the sort of graph illustrated below.

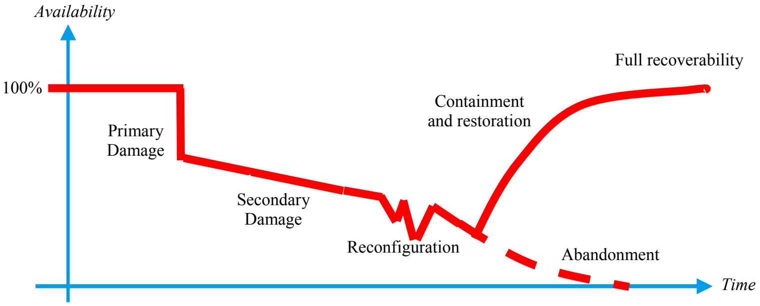


FIG.13 - AVERAGE AVAILABILITY OF A SYSTEM THROUGH TIME

This output can be used as comparison to a quantified recoverability metric - that a given function should have a minimum probability of availability after a given time post-hit.

Visual output starts with damage footprint diagrams colouring each attack location according to severity against a particular system, allowing easy identification of vulnerability hotspots.

From this point the analyst can interrogate individual attacks to establish how and why functionality is lost, before going on to evaluate possible changes that could improve survivability.

Iterative Improvements in Design

At any stage of design assessment, two questions are important:

1. Has the design met the requirements placed upon it?

2. How can the survivability of the design be improved?

Through the iterative process shown below SURVIVE can answer both questions and prove whether the chosen design changes are having a positive effect.

One measure frequently taken to try to improve a ship's performance is to reduce the spread of damage through the introduction of blast resistant structure.

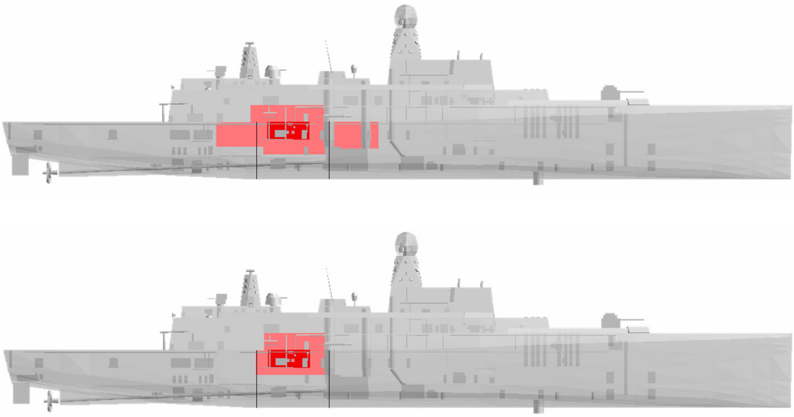


FIG.14 - EXAMPLE OF THE EFFECT OF BLAST RESISTANT STRUCTURE FOR A SINGLE ATTACK POINT

The aim of any measure is to reduce the damage footprint of a particular system of interest, as illustrated below.

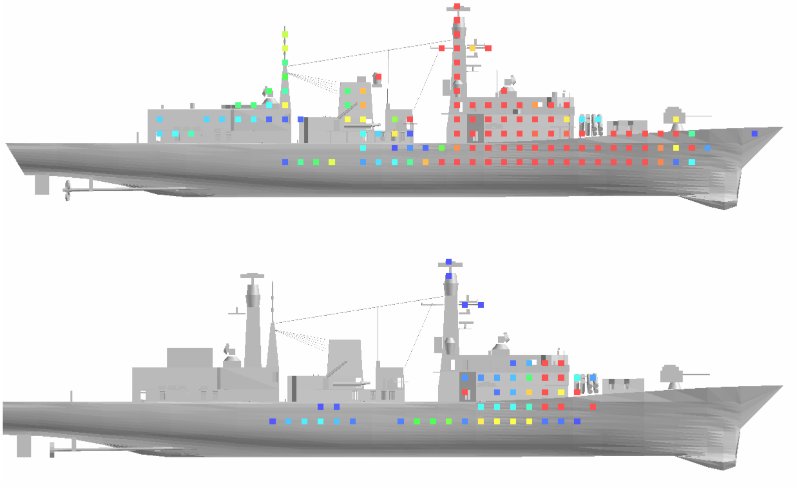


FIG.15 - EXAMPLE OF DAMAGE FOOTPRINT REDUCTION

It may be that a number of different options are identified that all contribute to a drop in vulnerability. In this case SURVIVE results can be used to trade off the options for improvement to inform the design team of a suitable way ahead given cost and risk.

Validation

SURVIVE benefits from many years of small and large scale trials conducted by the UK and international partners, some of which are shown below, as well as data coming from wartime incidents. These combine to establish the accuracy and credibility of SURVIVE's structural and functional damage prediction algorithms.

Detailed validation reports have been compiled for each of SURVIVE's primary damage algorithms, with secondary mechanisms either fully validated or verified against other accepted methods or data. Much of this validation work cannot be presented in open forum, but one example of the accurate prediction of blast spread is shown below. A high seas firing strike from a Sea Eagle on the County Class Destroyer ex-HMS Devonshire caused blast overpressure through several decks and several longitudinal subdivisions. The SURVIVE prediction of overall spread is very accurate, as is the level of structural damage caused (not shown here).

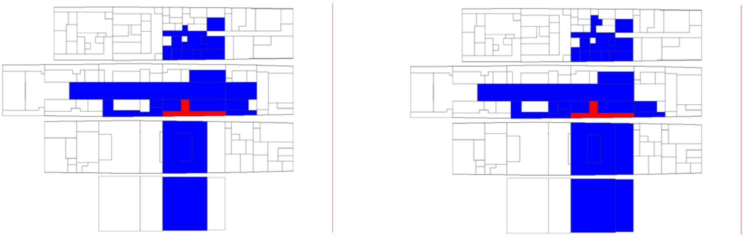


FIG.16 - COMPARISON OF ACTUAL (LEFT) AND SURVIVE PREDICTION OF BLAST SPREAD ON EX-HMS DEVONSHIRE

Case Study: Type 45 Anti-Air Warfare Destroyer

Common misconceptions are that assessment of whole-ship survivability once a design starts to mature is too slow a process to actually influence the developing design, and that data requirements are too onerous to allow sufficient detail to be considered. Experience suggests otherwise, as for the Type 45 Destroyer program. The SURVIVE team was involved with the Type 45 Destroyer program throughout the design process, performing a number of iterations of analysis, identifying weak points, evaluating change options and suggesting improvements at each stage.

Through good relationships built up between the vulnerability analysts and individual system designers, possible issues were resolved before they even became a formal part of the design. The fact that a survivability assessment is taking place focuses the mind on the provision of suitable redundancy and layout, so that these need not be seen as 'extras' that add to the cost. The existence of the assessment can offer other benefits. It is often the vulnerability analyst that has the best overview of the ship's systems at the early stages, and can advise on how to best handle their interdependencies and requirements.

A number of survivability features were introduced through many iterative stages of analysis. Vulnerabilities to single attacks were identified and mitigated or eliminated. SURVIVE's multi-strike ability was used to simulate multiple incoming threats leaving a platform able to keep fighting after one or more hits. Casualty assessments were performed to establish the level of protection afforded to crew. Magazine safety case assessments have informed the protection of magazines, both in terms of the effect of incoming threat weapons and the sympathetic detonation of the ship's own munitions.

Examples of the influence of SURVIVE in the design of Type 45 are:

- Armour to protect functional as well as magazine spaces;
- Sacrificial compartments that protect more critical spaces;
- Survivable distribution layouts and principals, such as the absence of a dedicated (and therefore critical) conversion machinery room;
- Blast resistant structure on key boundaries;
- Redundancy of command and communications assets;
- Identification of excessive redundancy in the internal network systems, leading to a simplification of the design and hence to real cost savings.