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Advances in ship survivability against underwater explosions

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Abstract. Mines, torpedoes and improvised explosive devices (IED) pose a serious threat to the survivability of naval combatants. Inasmuch, a major goal in the design of modern combatant ships has been to eliminate or at least reduce the devastating damage caused by underwater explosion events. Even though there has been extensive research performed on the various underwater explosion phenomena and their associated effects, effective shock testing and shock proofing strategies for naval ship systems have proven to be illusive. Through the use of modeling and simulation (M&S), live fire test and evaluation (LFT&E) and laboratory testing, general guidelines for the shock hardening of shipboard equipment and systems have been developed. In this paper, current aspect of ship survivability has been addressed and future direction is discussed.

Keywords: ship survivability; underwater explosion; ship shock modeling and simulation.

1. Introduction

Though commonly perceived as having its inception during the years of the Second World War, the use of underwater explosion (UNDEX) phenomenon as a destructive weapon in fact had its origins in the latter half of the 18th Century. Sparred torpedoes and primitive mines were employed in undersea attacks by both sides during the American Civil War. Floating or bottom moored mines, torpedoes as they had originally been called, were a low cost but highly effective means of disabling and sinking surface ships, with minimal risk to the ambusher. Primitive as they once were, submarines became more than mere novelties, transforming into silent and unseen killing machines. Tipped with torpedoes affixed to the end of a long spar, these explosive charges would detonate close a broad the unsuspecting enemy ship either by contact fuse or an electric impulse (Potter 1981).

In the decades that followed, underwater explosive devices grew in size while their delivery methods became much more effective NUWC(2006). Improved reliability and safety of these new weapons put the attacker in an advantageous position, being able to safely engage the unsuspecting enemy ship at some range. This combination of increased charge size, greater standoff distance and the exploitation of the physics of the underwater explosive phenomena resulted in undersea warfare tactics that brought unprecedented lethality to naval combat. The world wars of the 20th Century became the premiere showcase of this emerging strategy. Ships were sent to the bottom, or rendered

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utterly useless without having suffered a direct hit. German U-boats claimed more than 14.4 million tons of allied shipping losses during World War II alon.

Extensive structural model and live fire testing was performed in the 1950-70's using many of the decommissioned ships from the U.S. Navy's fleet after World War II. On Monday June 14, 1999 the Australian Collins class submarine, HMAS *Farncomb*, fired a Mark-48 war-shot torpedo at the 28 year old former Destroyer Escort *TORRENS* as shown in Fig. 1. With the Ticonderoga Class cruiser testing in the early 1980's, the U.S. Navy started a non-destructive full scale manned ship shock trial program to test the survivability and fight through capability of the ship and its crew. This practice has continued through each major surface combatant class of ship.

Empirical data backed out of the extensive tests and trials were used to formulate the governing equations for UNDEX and were later applied along with newly received Finite Element Analysis(FEA) techniques (LaCourse 2003). However, the use of FEA soon became limited by the expense and computing power limitations of mainframe computers in the 1970's.

In the last thirty years the capabilities of FEA software has come a long way. A significant cost reduction, substantial increase in computing power and overall ease of use of the FEA codes have driven models to become larger and more detailed (Thilmany 2000). Fig. 2 is a cutaway view of the USS WINSTON S. CHURCHILL (DDG-81) finite element model that was used in the whole ship

Fig 1. Mark-48 Torpedo War Shot

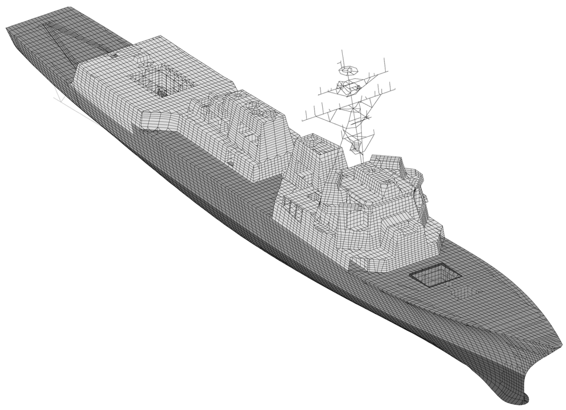

Fig. 2 DDG 81 finite element model (Harrington 2002)

shock trial simulation project conducted in conjunction with the June 2001 DDG-81 at-sea shock trials. The ship model consisted of more than 40,000 structural nodes, over 100,000 elements and nearly 250,000 degrees of freedom (Harrington 2002). Possessing many thousands more nodes, current ship models, such as that of the LPD-17, surpass 1,000,000 degrees of freedom (Shin *et al.* 2006).

2. Up-to-date trends

Over the past fifty years guidelines and specifications have been developed by the U.S. Navy for the shock testing and hardening of shipboard equipment and systems as found in NAVSEA 0908-LP-000-3010A and MIL-S-901D. In particular, OPNAVINST 9072.2 dictates that the complete ship system is to be tested by conducting "underwater shock trials". These shock trials are designed to test the ship in "near combat conditions" by detonating a large submerged charge at a series of standoff ranges and geometries with respect to the location of the ship. The response of the ship as a system is monitored, recorded and subsequently analyzed in order to determine the survivability of the ship as compared to a scaled-up design level blast. The lead ship of each class, or any ship that substantially deviates from other ships of the same class, is required to undergo these shock trials in order to correct any deficiencies on that ship as well as follow on ships of the class.

Typically a large charge is detonated at a preset distance from the ship or in the case of individual pieces of equipment, a barge test platform, at a specified depth beneath the surface in order to generate the desired shock factor. Fig. 3, is a photo taken during the DDG-81 ship shock trials, and shows what a typical shock trial event may look like. Velocity meters, accelerometers and strain gauges placed within the ship or on the barge record actual system response at the sensor location. These types of analyses are beneficial in gathering shock data, but come only after the ship has been built or equipment has been prototyped. Accordingly, they do not necessarily impact the final design of current ships in production at the time of the testing. The most obvious detriments in this form of testing are the cost, setup time, environmental concerns and inherent risk to ship, equipment and personnel.

It was reported that more than $70 million was spent on the U.S. Navy DDG-51 Class ship shock

Fig. 3 DDG-81 ship shock trial, june 2001 (U.S. Navy photo)

trials, from which 13 technically significant and 156 identified lessons learned were gained by conducting this series of traditional UNDEX ship shock trials (Lewis *et al*. 2003). The cost per item here seems staggering, and perhaps that is indeed the point that we should take from this. Fortunately, in this case the ship shock trials not only served as a means to satisfy the statutory requirements but furthermore yielded the added benefit of proving out an evolving alternative to LFT&E shock trials, namely the ability to use computer modeling and simulation to predict the response of a surface ship subjected to an attack in an UNDEX environment.

Computer modeling and simulation efforts performed, including the research, finite element modeling, simulation and subsequent analysis, generally cost only 10 to 15 percent of the total at sea shock trials expenditures. In addition to the impressive cost benefit, computer simulation also permits for the realistic testing of a ship's survivability without placing the ship, equipment or crew in danger. Furthermore it offers the ability to conduct virtual attacks on the ship in a nearly limitless number of attack geometries. Mitigation of the environmental impacts of open ocean full ship shock trials is also negated by the use of M&S.

The underwater shock research has lead to a sound ability to successfully model naval surface combatants using the finite element method and place them under simulated attack in a virtual UNDEX environment (Shin and Schneider 2003). The analysis of the DDG-81 ship shock trials demonstrates that modeling and simulation can be used to accomplish much of what was once reserved for LFT&E programs. Fig. 4 shows the coupled fluid-structure model used in the DDG-81 shock trial simulations.

The finite element model of the ship is joined with a corresponding fluid mesh model. The nonlinear dynamic analysis code LS-DYNA is used to solve for the structural response of the model at designated nodal locations throughout the ship. The Underwater Shock Analysis (USA) (DeRuntz 1996) code calculates the transient response of the ship's wetted surface at the fluid structure interface.

A typical veritcal velocity time repsonse plot of a node/sensor pair from the DDG-81 ship shock trial simulation effort is provided in Fig. 5. In looking at the plot, the red data curve corresponds to the actual measured data from a ship shock trial veolcity meter guage. The blue data curve is the

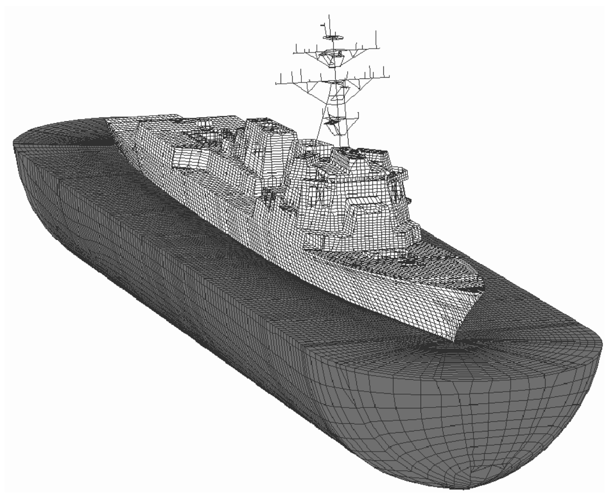

Fig. 4 USS WINSTON S. CHURCHILL Coupled fluid-structure model (Shin and Schneider 2003)

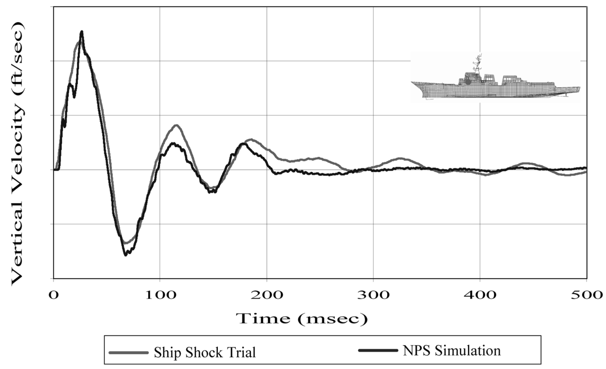

Fig. 5 Vertical velocity response of DDG-81 node/sensor Pair (Shin and Schneider 2003)

simulation data obtained using the coupled fluid-structure model depicted in Figure 4. The red dot on the ship image represents the genreal location at which the sensor was mounted during the shock trial and its correpsonding node in the finite element mesh. This plot shows excellent correlation between the measured data and the simulation model data. Notice that the intial peak matches nearly perfectly. This transient response in the early time of the UNDEX event is where the majority of the enrgy is delivered to the ship system. Only later in the time history does the presence of damping take effect to reduce the response (Shin and Ham 2003).

3. Broadening our horizon

With successes in modeling and simulation of the full ship shock trial, some may venture to dismiss the need for LFT&E, stating that everything can be done by modeling and simulation alone. However, this is not the case. The attack on USS COLE (DDG-67) off of Yemen in October 2000 is a stark reminder of the reason why we cannot become complacent with what has been accomplished to date. Even though the USS COLE is of the same of ship class as the DDG-81, the analysis completed in support of the DDG-81 ship shock trials is only of negligible usefulness in understanding the shock phenomena introduced by the explosion of an IED in the small boat attack at the ship's waterline.

During a ship shock trial the entire ship system, that is the ship structure, the equipment, weapons and subsystems along with the crew, all endure a blast from a charge at some set distance from the ship. Thus far it has been demonstrated that it is possible to accurately simulate the response of a ship subjected to an underwater explosion which is considered to be a far field shock, at a standoff distance of 10-100 charge radii (Shin 1996). Yet in the case of the USS COLE attack the charge was detonated almost right up against the hull. In order to accurately model this scenario, the approach, problem formulation and analytical solvers necessary are of markedly different set than the ones used in analyzing the traditional UNDEX event experienced in the full ship shock trial. Penetration, fluid flow and failure effects become pronounced in this type of investigation.

In redefining the role of modeling and simulation, and for that matter the direction in which the entire UNDEX field is to proceed, all surface ship threats, not only those evaluated in the traditional shock trial scenario will need to be accounted for. To date, full ship shock testing and simulation has only truly addressed the traditional or far field shock. This case has been largely been investigated through use of complex finite element models, and solution techniques employing such methods as the Doubly Asymptotic Approximation (Geers 1978). For near field shock and contact scenarios simpler, beam models have been generally used to recover the guider strengths and effects of the keel global bending, yet recent work has shown that with the greater detail given in high fidelity FEM ship model, localized effects such as surrounding a scuttle in the deck can be found during investigations such as ship whipping analyses.

4. The way ahead

A variety of threats bring unique problems to the surface ship UNDEX problem. The conceptual flow chart in Fig. 6 is designed to act as a though process decision matrix for surface ships exposed to an explosion event. This figure lists key decision elements necessary in developing a tailored UNDEX problem attack plan. Factors such as the shock target designation, threat type, explosion

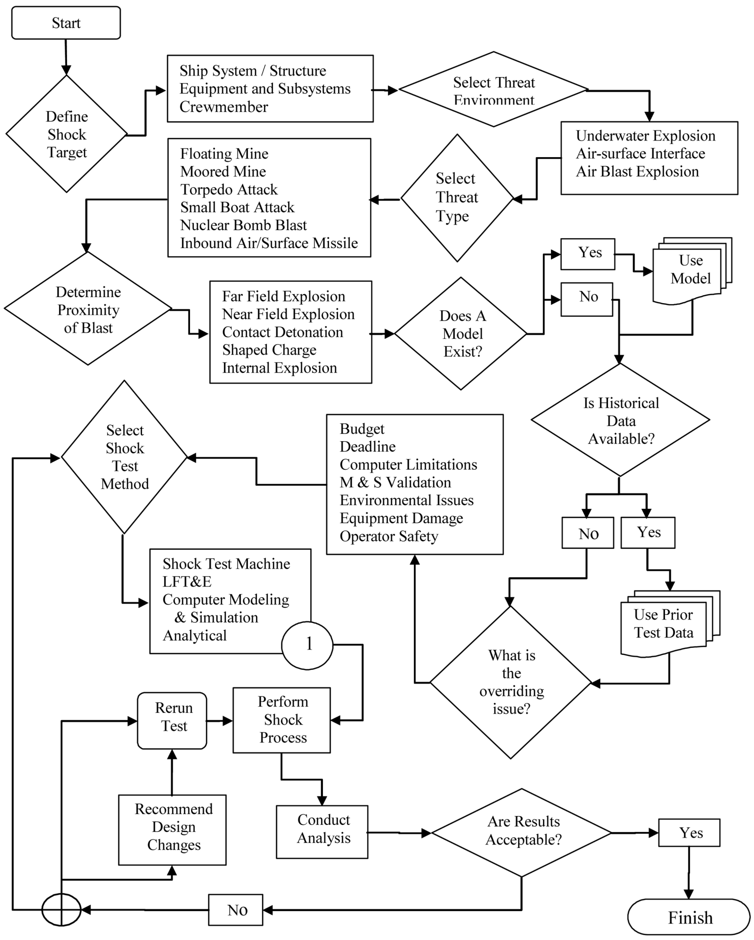

Fig. 6 Threat based surface ship shock analysis decision making tool

environment characteristics, and engineering method constraints, all have a role in determining which type of shock testing and verification should be used to glean the most useful response data corresponding to the particular UNDEX phenomena being investigated. The ultimate goal is to ensure that a ship is survivable once constructed and delivered to the Fleet. The most cost-effective way to accomplish this is to make survivability an integral part of the design rather than a parameter to test once completed.

We currently posses many tools with which to gain knowledge about testing of equipment: the floating shock platform (FSP), paddlewheel, submerged shock test vehicle (SSTV), a variety of complex shock test machines, vibration tables, drop test stands etc. In addition to these devices used to do experimental tests, there are also analytic tools such as the Dynamic Design Analysis Method (DDAM). Based on a threat matrix, such as the one outlined in Fig. 6, the design team will select the best test method or design tool in order to gain the greatest return on investment. Full ship shock trial testing and simulation has been the mainstay in determining ship survivability yet this is neither cost effective nor practical from the design standpoint. Location specific, near field shock evaluation through LFT&E and simulations can close the gap between the post production full ship shock trials and other existing shock qualification methods. The question becomes which of these tools will provide sufficient feedback in a timely manner to the ship design team during the final iterations of the design spiral.

For example, in the case of a MK 48 torpedo threat, the shock survivability investigation would most certainly center on such phenomena as ship whipping, water jetting and other close-in damage mechanisms. Inasmuch, the methodology used for a far field shock analysis would be inappropriate and another analysis tool would need to be selected from the options listed in Fig. 6, which ties into Fig. 7 under the "Shock Test Method" selection decision block as "circle one".

Once the general shock testing methodology has been selected, a detailed analysis of what particular process might be best suited should be examined. In this phase, questions of cost, time, and desired level of detail in the end result must be addressed for that particular method. A decision chart for this stage might look something like Fig. 8, which deals with selection of the appropriate

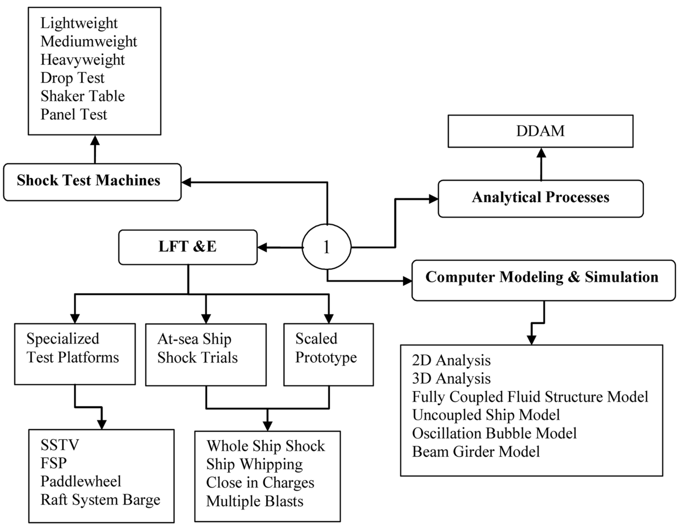

Fig. 7 UNDEX Shock testing toolkit

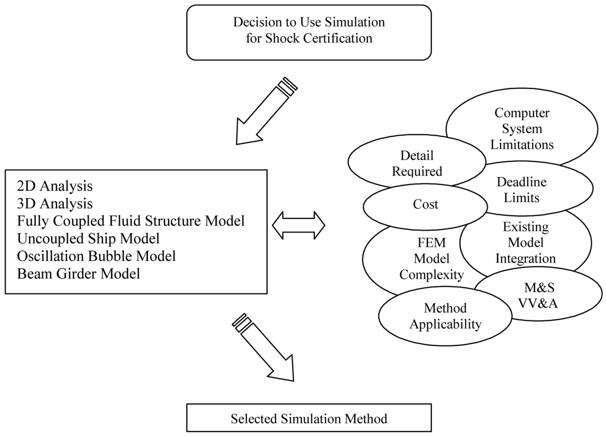

Fig. 8 Influences on simulation code selection process

simulation tool for a full ship shock trial analysis.

The UNDEX field of research has come a long way since the first tests were conducted using simple structural models. Inasmuch as has been learned, one thing continues to resurface – the fact that there is no one way to perform an all encompassing test or to run just one type of simulation that can provide all of the solutions. The UNDEX phenomena are many and perhaps the best method in combating this multifaceted problem facing ships is to attack it with a myriad of methodologies. Taking the best of each of the testing techniques and combining them into an interactive decision based set of tools, or toolbox, would enable the end user to tailor the solution to the specific goal at hand in order to most effectively design and certify the ship shock hardened and ready for sea service.

5. Conclusions

In order to meet the demands of the evolving UNDEX environment we must continue to apply the lessons learned from the past century of shock trials, equipment testing, experimentation, simulation and live fire testing & evaluation. By exploiting present and future technologies and tailoring their application by selectively using the most appropriate of these tools in solving specific threat scenarios we can further strengthen ships against the menacing UNDEX shock threat through incorporation of shock survivability in the design phase. With the correct selection and application of appropriate modeling, simulation and testing methods, the ship design process can be positively impacted to further enhance shock survivability from the keel up.

Acknowledgements

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