LAGRANGIAN HYDROCODE MODELING OF UNDERWATER
EXPLOSIVE/TARGET INTERACTION

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Preliminary results are described for an application of the Lagrangian hydrocode DYNA3D in modeling the early-time interaction of an underwater close-in explosion with an externally stiffened, curved plate. The problem was terminated when element distortions reduced the time step to unacceptably small values.

The Johnson-Cook constitutive and damage model was used for the steel plate and stiffener frames. Use of this material model allowed the frames to fail at their base and separate from the plate, relieving the stress in the target plate. Failure in the steel plate was shown to initiate directly under the explosive charge, but model improvements may alter this result.

Shell elements were employed for the steel to properly model bending of the plate and frames, and to decrease problem size. A total of less than ten thousand elements (continuum and shell) were employed in the complete model; this was made possible largely through the use of non-reflecting boundary conditions.

INTRODUCTION

The analysis of close-in, underwater explosively driven fluid-structure interaction is a capability that has only recently become available due to the incorporation of structural analysis capability in hydrocodes. These sophisticated codes are capable of modeling not only fluid-structure interaction but also cavitation, high strain rate material behavior and material failure.

Fluid-Structure Interaction

Underwater explosions (UNDEX) of bulk charges in proximity to a target results in fluid-structure interaction (FSI). It is common for the discussion of UNDEX FSI to be separated into two categories: shock-target interaction and bubble-target interaction. It is also convenient

to subdivide each of these into local and global target response. Close-in underwater blast effects local target response, while global target response is due to far-field detonation. The separation of shock and bubble effects is valid for global target response, but these phenomena are not readily distinguishable for close-in blast (local structural response).

Structural response to shock waves is a high frequency phenomenon, usually measured on a microsecond or millisecond time scale. Response to bubble dynamics is a much lower frequency phenomenon (vibration), often measured on a millisecond or second time scale.

Fluid-structure interaction capability is available in many computer codes to some extent. In the field of computational UNDEX FSI, structural analysis capability has only recently become available.

Computational Structural Analysis

The targets that underwater warheads are likely to engage are generally engineering structures; that is, comprised of relatively thin walls, beams, and masses. In order to properly and practically model the dynamics of general engineering structures, special computational attention must be focused on the structure. Thus many special purpose "structural analysis" codes have been developed over the last few decades.

If simple continuum ("brick" or "volume") elements are used to discretize a plate, several of these elements must be used through the thickness to properly model the bending of the plate. Since the stresses in a general element are commonly defined for only one point per element, a plate in bending defined by one element through the thickness would compute a zero bending stress, instead of showing that the exterior side is in tension and the interior in compression. As more elements are added through the thickness, the bending stress profile through the thickness (a series of steps) will more closely approximate the true slope profile.

In codes that simulate explosive-target interaction, the time step is based on the wave velocity across every element of the computational mesh; the minimum of every "element time step" determines the global time step. Therefore, if several elements are used to discretize the thickness of a thin plate, a typical element time step (and correspondingly global time step) will be vanishingly small. Furthermore, practical limits on the aspect ratio of elements forces the non-thickness dimensions of the solid elements to decrease as the number of through-the-thickness elements increases. This results in the number of elements that actually discretize a given thin plate being unreasonably large. The combination of unacceptably small time steps and an unreasonably large number of elements results in prohibitively expensive and impractical computational efforts.

Structural elements overcome these limitations. In structural analysis, a thin plate is modeled using "plate" (flat) or "shell" (curved) elements. A typical shell element has no apparent thickness, but the mechanics of bending is incorporated into the element, based on an implicit thickness. The element time step in a code incorporating structural elements is based on the planar dimensions of the elements and is therefore much larger than that using continuum elements. In fact, if structural and non-structural elements are used within the
problem domain, the global time step is probably based on elements within the domain that are not structural. Furthermore, the aspect ratio limitations now apply only to in-plane ratios, allowing elements to be much larger. Larger and fewer elements, coupled with much larger time steps, allow reasonable computations of such structural problems.

A limitation introduced by the application of structural elements in explosive-target interaction problems is that wave propagation through the thickness of a thin plate is no longer modeled; in effect, a wave is instantaneously propagated through a plate. In problems where the structure of a wave propagating through the thickness of a plate can be expected to play a significant role in the plate dynamics (e.g. spall), the employment of shell elements is not appropriate.

Computational Methods

Many methods are available for computationally analyzing the effects of underwater explosions on targets, but they can be categorized into general-purpose and special-purpose methods. No major simplifying assumptions are made in general-purpose methods, but special-purpose methods are more computationally efficient, focusing computational effort on a specific target response phenomenon (either shock- or bubble-structure interaction).

The capability for properly modeling the dynamics of structures and fluids is vital in all of these methods, as is the interaction between the structure and the surrounding fluid. The methods are described in detail in reference [1].

General-Purpose Methods. The general-purpose methods are commonly termed "hydrocodes," although these codes have long since ceased to have simply "hydrodynamic" descriptions of material behavior. Current hydrocodes are capable of modeling not only detonation and hydrodynamic flow (fluid dynamics), but also material strength, plasticity and failure (solid mechanics). Some hydrocodes have even implemented the capability to model structural mechanics (a subset of solid mechanics), allowing them even wider applicability. It will be shown that this structural analysis capability is crucial to the practical modeling of underwater explosive-target interaction.

Hydrocode analysis is only a small portion of the field of computational mechanics; Computational Fluid Dynamics (CFD) and Computational Solid Mechanics (CSM) are rather highly developed yet still largely independent disciplines whose primary concerns are the mechanics of fluids and solids under static, quasistatic, steady-state or dynamic conditions. Hydrocode analysis concerns itself with these same disciplines but only under such highly dynamic conditions (e.g. detonation) that shock wave propagation is significant. As such they are exclusive to neither Solid Mechanics nor Fluid Dynamics, and fulfill a requirement that neither classical Fluid dynamics nor Solid mechanics codes are suitable for. Basically, hydrocodes make fewer simplifying assumptions than either classical CFD or CSM codes; they numerically solve the more fundamental equations of Continuum Mechanics in their most general form (as distinguished, for example, from the Navier-Stokes Equations of classical Fluid Dynamics). Here the entire domain of interest is discretized into many elements or cells. As with almost any Computational Mechanics tool, the material models (particularly failure

in solids and high explosive equations-of-state) are considered the "weakest-link." Hydrocodes are mainly applicable to, and developed for, the military industry and can analyze highly dynamic problems involving reactive flow (e.g. detonation), shock waves, impact, etc. Due to stability restrictions, the time step is generally dependent on the smallest element/cell side length.

Shocks are generally "smeared" over several elements to avoid problems with discontinuities; as a result computed peak shock pressures are lower than true values, but impulses are realistic. Since structural response is driven by impulse and not peak pressure, it is generally appropriate to compute smeared shocks in underwater explosion-target interaction.

The Lagrangian, Eulerian, Coupled Eulerian-Lagrangian, and Arbitrary Lagrangian-Eulerian methods are examples of general-purpose methods.

In the present analysis, the Lagrangian hydrocode DYNA3D was applied to an early-time explosive-structure interaction problem. The unique feature of DYNA3D that made it particularly useful was its extensive structural analysis capability; although only shell elements were employed for the structure, the model could be extended to include beams, springs, and masses.

Special-Purpose Methods. To increase efficiency and practicality, special purpose methods have been (and are being) developed. They incorporate simplifying assumptions allowing computational effort to be focused on one specific phenomenon at the exclusion of others. The Shock-Structure (global shock-structure interaction) and Bubble-Structure (global bubble-structure interaction) special purpose methods are available or under development. Strict attention must be paid to the limits of applicability of these methods.

PROBLEM DESCRIPTION

The Lagrangian hydrocode DYNA3D [2] was chosen to simulate an early-time, close-in UNDEX FSI event because of its extensive structural analysis capability. Due to the close-in nature of the problem, no special-purpose code is applicable. DYNA3D has not only shell elements but beam, spring, mass and damper elements as well, all very useful in advanced modeling strategies. Large-strain shell elements were used for all steel parts (target plate and stiffeners), while 8-node continuum elements were used for all water and explosive regions.

As shown in Figures 1 and 2, a 100 pound charge of aluminized explosive was placed directly above an external stiffener of the curved target plate. The quarter symmetry shown in Figure 1 allowed a greatly reduced problem size. A more appropriate model might entail half symmetry (including the quarter of the problem on the other side of the central stiffener), since possible buckling behavior of the stiffener directly under the charge is not accounted for in the present model.

The target was a high-strength curved steel plate with external stiffeners. Although only 60 degrees of a full cylinder was discretized, the symmetry results in a 120 degree model. The Johnson-Cook strain-rate and temperature-sensitive plasticity model was employed for the steel, and the corresponding failure model was added.
interface between the hull elements and the stiffener elements was formed by a simple merge of common nodes; therefore the weld is assumed to be as strong as the steel plate comprising the stiffeners.

It has been previously shown [31 that external stiffeners must be finely zoned near the weld to allow for stress localization and potential failure. If the stiffeners are coarsely zoned, the stress does not localize, failure may never occur, and the stresses in the target plate are allowed to localize, causing premature failure.

The water was modeled with a Mie-Grueneisen equation-of-state; this is usually considered appropriate for models in which the details of the shock in the water are not of primary concern. Along all exterior surfaces of the water (except at the steel/water interface), non-reflecting boundary conditions were applied. This allows a shock wave to exit the problem domain with little or no reflection, permitting a drastic reduction in problem size.

The explosive products were modeled with the standard JWL equation-of-state. A slideplane (contact surface) was placed between the explosive and the stiffener below it; the slideplane extended to the edge of the water region on all sides and therefore separated the water and explosive above the tops of the stiffeners from the water and steel below. The slideplane was required in this problem since the explosive sits directly on top of a stiffener; had the elements been merged, the steel that shares nodes with the explosive would be unrealistically stretched with the expansion of the explosive gases.

The problem domain included a total of 8430 nodes. These nodes defined the corners of the 6048 continuum elements and 1785 shell elements.

RESULTS

The problem ran to 3.3 milliseconds in just over 6000 cycles (roughly ninety CPU hours on a MicroVAX) before element distortions reduced the time step to unacceptably small values; at this point the run was manually terminated. Figure 3 shows the explosive and target plate at that time.

As seen in Figure 4, failure at the base of the external stiffeners initiated close to the explosion and propagated rapidly along the base. This failure relieved the concentration of stress in the target plate at the plate/stiffener interface. Figures 5 and 6 detail the time histories of stress and strain in the failing elements, and show the propagation of the failure.

Shortly before the time at which the run was terminated, failure in the target plate was seen to initiate directly under the explosion, as shown in Figure 7. Figures 8 and 9 detail the time histories of stress and strain of the failing element. The artificial strength of the central stiffener associated with the symmetry boundary condition quite likely contributed to the failure; in effect, the stiffener acted as a "punch" and concentrated the stress in the target plate.

The damage shown in the Figures does not correspond to the final damage that a computer code would predict, since the problem was prematurely terminated. The explosion bubble has not fully expanded, and the bubble collapse would inflict additional damage to the target.

DISCUSSION

The extension of the current quarter-symmetry model to half-symmetry, to take into account the possible buckling behavior of the central stiffener, is a logical step toward the creation of a next-generation model. The failure of the target plate directly under the explosion may be artificially promoted by the added strength of the central stiffener (its lack of buckling capability). If the central stiffener does buckle under the application of the load, a relief in stress in the target plate will be apparent.

The validation of this model is of primary importance. To accomplish this, a refined model must be compared with experimental data. The current model must undergo mesh refinement studies until the computed target response is no longer a function of the computational mesh.

Longer duration modeling of this geometry might be accomplished through employment of a Coupled Eulerian-Lagrangian (CEL) code, in which the target would be discretized as Lagrangian and the water and explosive would be Eulerian. The thin cross-section of the stiffeners, however, presents a modeling difficulty, in that a very fine Eulerian mesh is required to properly model the coupling between the Lagrangian and Eulerian meshes.

This interaction problem may be better solved by an Arbitrary Lagrangian-Eulerian (ALE) code with structural analysis capability, although no such code yet exists. The target structure would be forced to remain Lagrangian, while the water and explosive would be allowed to distort in an ALE fashion.

REFERENCES


Figure 1. Initial configuration (forward symmetric half not shown).

Figure 2. Full initial configuration (water elements not shown).


Figure 3. Full final configuration (water elements not shown).

Figure 4. Full configuration of final target damage.
Figure 5. Time history of effective stress for closest failing stiffener element.

Figure 6. Time history of effective stress for neighboring stiffener elements showing failure propagation.
Figure 7. Time history of effective plastic strain for closest failing stiffener element.

Figure 8. Time history of effective plastic strain for neighboring stiffener elements showing failure propagation.

Figure 9. Time history of effective stress for target element directly under explosive, showing onset of failure.

Figure 10. Time history of effective plastic strain for target element directly under explosive.