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Numerical simulations and precision impact testing for the development of an UNDEX response validation methodology

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Abstract

The assessment of the response of naval vessels to underwater shock creates a need for tools that can analyze and design such systems to withstand underwater explosions (UNDEX). The short-duration dynamic response of simplified structural components to an UNDEX loading was investigated. A methodology has been developed by which the response of a simplified structural component to UNDEX can be validated through the use of precision impact testing and numerical simulations. An iterative process was used where an UNDEX response, determined through previous results, preliminary UNDEX simulations, and impact simulations, leads to the parameters necessary for a precision impact test that generates an equivalent response. Precision impact tests were performed, and the results correlated with the impact simulated data. The results from an UNDEX test were compared with the predictions from the validated numerical code. The simplifications to the structural component included these tests and simulations performed with a rectangular flat panel. The numerical simulations were three-dimensional, solved explicitly, and included either the impact loading environment - a hybrid impactor with an initial velocity - or the UNDEX loading environment - a plane shock wave applied to the surface of the target structure. Since only the short-duration response was of concern, later time effects, such as gas bubble effects, were ignored. Although the methodology was developed to use multiple iterations, the scope of the study only included one set of precision-impact tests on each type of material, one UNDEX test against the aluminum panel, and two UNDEX tests against the composite panel. Once the methodology using precision shock testing and numerical simulations to validate the UNDEX response had been developed, it was applied to a "design-for-shock" procedure.

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1.0 Introduction and Objectives

Underwater explosion (UNDEX) tests are costly and hazardous, generating pressure-time load histories that are not well quantified, response data that are difficult to acquire, and the tests may not be repeatable. Nevertheless, a validated approach to accurately predict the short duration dynamic response of a structure subjected to direct UNDEX pressure wave loading does not exist. Therefore, a more cost-effective method to validate the UNDEX response without using the "shock qualification" tests was sought. Krauthammer, et. al. (1996) suggested that precision impact testing can be used to produce peak loads, rise times, durations, and spatial distributions similar to those produced by explosions in air. For this study, the concept of equivalency between in-air explosive and impact loading was expanded to include UNDEX loading. It was postulated that the short duration dynamic response of structures subjected to UNDEX direct pressure wave loading can be reproduced by precision impact loading. Once equivalency is demonstrated, it is proposed that precision impact tests can be used to assess structural integrity of components subjected to direct pressure wave UNDEX loading. This investigation included two important aspects - precision tests and numerical simulations. These were combined to form the unique assessment methodology. Here, a generic UNDEX event is considered, and the concept could be applied to any far-field UNDEX problem. A more comprehensive coverage of this work can be found in O'Daniel (1998).

The primary objective of this investigation was to explore the existence of a relationship between short duration dynamic structural response to UNDEX and to impact. Further, if such a relationship could be found, to develop a methodology to demonstrate an equivalency in structural response between impact and UNDEX testing. The impact tests and simulations were used to produce a response that envelopes the UNDEX response, matching important trends and characteristics. For this study, equivalency was assumed when structural strain time-histories produced by the UNDEX and impact loadings were equivalent. The second objective of this investigation involved the validation of a numerical code by precision impact tests. This was an essential part of the UNDEX-impact equivalency methodology. The methodology was developed using an aluminum panel, and then it was demonstrated on a composite material panel to show that the developed procedures are independent of the structural material. Finally, the validated numerical code was used to predict structural responses in future UNDEX tests, and to demonstrate the effectiveness of this methodology by comparison with test data.

2.0 Methodology

Because both UNDEX and impact loadings are complicated, the component geometry was simplified to facilitate the UNDEX-impact equivalency. The structural component was simplified to a rectangular flat plate, which was used for the numerical models and tests performed in this investigation. It was assumed that the explosive was located far enough away from the component so by the time the direct pressure shock wave strikes the structure, the wave was planar. In addition, it was

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assumed that the component was submerged in an infinite fluid, implying that pressure waves reflected from other surfaces could be neglected. In this investigation, only the elastic portion of the short duration dynamic response was considered. Therefore, yielding, plastic behavior, and failure conditions and behavior were not included in any of the simulations. A linear elastic, isotropic constitutive model was used for the aluminum panel, and a linear elastic, orthotropic material model was used for the majority of the composite panel.

The methodology consisted of four key parts that, when combined, achieved the initial objectives. First, a structural short duration dynamic response had to be defined using the characteristic parameters (charge size, standoff distance, and water properties) of the UNDEX event under consideration and the characteristic properties of the structural component. The precision impact test could be developed once the UNDEX-induced response in the structural component had been determined. Using an iterative process, an equivalence was established between the original UNDEX response and the simulated impact response. Second, it had to be determined that the derived impact response represented "real" physical behavior. This was accomplished by performing precision impact tests using the developed impact parameters. These tests validated the numerical impact simulations. Third, the UNDEX response was correlated through the same procedure, comparing the results of the simulation to scaled UNDEX test data. Finally, an assessment of the results from the methodology was carried out to determine if the process had indeed established an equivalency between the UNDEX and impact events. Each of these parts is described in more detail in the following paragraphs.

An initial simulation of the UNDEX configuration was developed to predict the short duration dynamic response that was then used to prescribe the parameters of a precision impact test that would produce an equivalent response. The most important part of this portion of the process was determining the UNDEX loading environment and, generally, the range of response of the structural component to that loading environment. After determining the loading environment, the result was a pressure time-history that can be applied to the structure. Similitude equations were used to generate the pressure-time history using the parameters of the explosion. In parallel, the component to be subjected to the UNDEX loading was selected, and a finite element model of it generated. The approximated plane wave loading and the component model were inserted into the explicit fluid-structure analyses to produce the UNDEX short duration dynamic response. Preliminary simulations of the UNDEX problem were performed to determine the levels of strains and accelerations the structure experienced during the UNDEX event.

Once the structural response to the UNDEX load was determined, an impact event that reproduced an equivalent response was needed. The preliminary response contained strains, and strain rates within the target panel that were used to reproduce the equivalent response with the precision impact test. Therefore, the parameters for the precision impact test had to be determined through the comparisons of results of the simulations of the UNDEX and impact events and the use of engineering judgement and supporting numerical simulations. Developing the precision impact test included: selecting the parameters for the test, and simulating that test to

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determine if the generated parameters produce a structural response that was equivalent to the UNDEX response. The parameters of the impact test that could be varied were the impact velocity and the characteristics of the impactor, including geometry, mass, mass distribution, stiffness, and stiffness distribution. It was important to distinguish between the parameters of the test that can be adjusted and the parameters that have to be fixed in order to generate the desired response from the structure. The iterative process of adjusting the parameters and simulating the new configuration was repeated until the precision impact simulation response and the UNDEX response were equivalent. Once the equivalence was established numerically between UNDEX and impact, it had to be determined whether the simulations of a precision impact test and an UNDEX test represented reality.

A picture of the impact testing machine, including an aluminum test panel is shown in Figure 1. The impactor was raised, compressing accelerator springs. When released, it fell to strike the top face of the test panel. A catch mechanism ensured that the impactor was only allowed to strike the entire face of the structure once. Tests were conducted at impact velocities of up to 162 in./s. The same composite test structure was used for the UNDEX tests. The shock waves propagated through the water, striking the structure, causing the structure to respond.

The precision impact test and simulation were generated in parallel so their results could be compared and the numerical code validated, as required by the third objective of this investigation. The precision impact machine and impactor were designed and fabricated to accommodate the impact parameters that have been generated from the numerical equivalency process. Precision impact tests were conducted and the measured response was compared to simulation results. All the data were analyzed from both the simulation and precision impact test, and a decision made as to whether the process provided the intended and needed results. If a correlation between impact test and simulation did not exist, it had to be determined whether the difference stems from inadequacies in the simulations or if the precision tests did not produce the response expected. If the precision impact simulation was altered to obtain better correlation, the new configuration had to be analyzed to determine if the correlated impact response was still equivalent to the original UNDEX response.

Once the precision impact test was correlated with the numerical simulation, the simulated UNDEX model had to be correlated with a scaled UNDEX test, providing a basis by which confidence was established in the numerical code's ability to simulate the fluid-structure interaction modeled in this investigation. The process for the UNDEX simulation was the same as was done for the precision impact simulation. The UNDEX test was performed, the UNDEX simulation was generated, and their results were compared. The result of this part of the methodology was a code that could be used to model the UNDEX event and a correlated response that can then be compared to the precision impact response.

The methodology was completed through the multiple comparisons between simulation and test results for the UNDEX and impact configurations that have been outlined. The final assessment of the methodology determines the feasibility of the results and whether the equivalency has been established to the required level, or if

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further iterations of the methodology are necessary.

3.0 Numerical Simulations

As was stated above, the loading caused by an underwater explosion contains similar features to impact loading. Blast and impact analyses share several common characteristics. Inertia effects must be considered for both types of problems. Wave propagation effects are needed to account for the interaction of stress waves between different materials and separate parts of the system. These effects lead to the use of explicit time integration to solve the problem, as was used for the previously performed impact simulations. Once the explicit finite element code LS-DYNA was validated for short duration dynamic loading, the UNDEX tests were simulated using the same code and previously used procedures. This provides an alternative to attempting to solve the problem with a theoretical or semi-empirical solution.

The finite element models were discretized with a combination of eight-noded, three-dimensional continuum elements and two-noded, three-dimensional beam elements. The continuum elements were used to represent the test panels, steel support structures, impactors, and the fluid medium. The beam elements were used to model the bolts connecting the panels to the steel supports. The modeling of the panel-support connection is discussed in more detail later in this chapter. Both types of elements are formulated to handle both material and geometric nonlinearities, and therefore are valid for large displacements and large strains.

Parametric studies were performed to determine the necessary mesh density in the panel and support structure. The amount of elements used was systematically increased until a difference of less than 1.0% occurred between iterations of the simulation. A similar parametric study was used to determine the amount of water that had to be modeled around the structure during the UNDEX simulation so spurious reflections did not interfere with the structural response of the structure during the time under consideration.

The finite element mesh used for the structure is shown in Figure 2. This mesh was used for both the impact and UNDEX simulations, adding an impactor for the impact configuration and surrounding the structure with solid water elements for the UNDEX configuration. The geometry of the impactor was attained through the determination of the impact parameters, and through the observation of the impact test results. Once initial results had been obtained, it was determined that more of the impactor support structure had to be modeled in order to have correlation between test and simulation data.

4.0 Results

This section contains some of the significant results from the tests and simulations, and provides the comparisons needed to investigate the feasibility of the equivalency concept and to demonstrate the methodology. More complete results can be found in O'Daniel (1998). The strains were the primary characteristic used for the comparisons, and strain rates were also compared between UNDEX and impact

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events.

The results of the impact simulations and tests compared well once some modifications had been made to the finite element model. Additional portions of the impactor needed to be modeled in order to more accurately reproduce the behavior due to the distributed nature of the impactor. A comparison between the aluminum impact test and simulation of the centerline longitudinal strains on the bottom of the panels is shown in Figure 3. The model captured the general behavior at this position, but overpredicted the peak strain. A second hit occurred between the centers of the impactor and target panel at about 2.25 msec. This was due to the edges of the impactor still being in contact with the panel when the center of the panel rebounded. The strain was underpredicted after the second hit, but the simulated strain paralleled the test data out to 5.0 msec.

The actual pressure loading experienced by the test structure during the UNDEX test was very close to the simulated pressure loading calculated with the similitude equations. It was estimated from the dimensions of the pond and the acoustic wave speed in water that there would be approximately 2.5 msec of "free" time before reflections entered the test data. The centerline longitudinal strain responses of the test and simulation are compared in Figure 4. Much larger strains are seen initially in both simulations, and the correlation is not that good at this position. After 1.5 msec, both simulations deviate from the experimental results. This was sooner than the anticipated time of approximately 2.5 msec, when reflections were thought to enter the measured data.

The correlation is much better away from the centerline, as evidenced by the comparison made at 7.0 inches (Figure 5). The general path of the measured strain was followed more closely without the large oscillations at the beginning of the time history. The longitudinal strains at the other offset positions reflected the same closer correlation when compared to the center position.

The over prediction of strains was partially attributed to the inability of the urethane constitutive model in the composite to dissipate the high frequency energy components. The higher strains in the simulations were also partially due to the difference between the measured transient pressures and those used in the simulations. Both the differences in pressure magnitude, as well as the spatial distribution of pressure over the plate contributed to the discrepancy.

The initial and final UNDEX-impact comparisons for the centerline longitudinal strain in the aluminum panel are shown in Figures 6 and 7. Initially, the peak positive strains are approximately equal between UNDEX and impact, and the initial period of response was also nearly equal. The test data exhibits a compressive behavior at 0.5 msec that was not reproduced by the simulation. In the final comparison, the UNDEX strain was much higher than the impact strain.

The alterations made to the simulations in order to validate the response against test data worsened the equivalency. According to the methodology, another sequence of impact tests would be necessary with new impact parameters, but those tests were beyond the scope of this investigation.

A comparison of the final UNDEX versus impact strain in the composite panel is shown in Figure 8. The peak positive strains compare well, but again the impact

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did not reproduce the initial compressive response seen in the UNDEX simulation. More investigation needs to be performed into developing a representative constitutive model for both the rubber foam used in the impactor, as well as the rubber that is contained within the composite.

5.0 Conclusions

The UNDEX-impact equivalency concept was shown to be feasible within the limited scope of this study. The foundational work performed here revealed that the equivalency methodology can reproduce some of the important characteristics of the short duration dynamic UNDEX response, but much more work is needed to determine the extent of the methodology's applicability. The methodology worked significantly better for the composite material. The final strain comparison between UNDEX and impact responses for the aluminum panel was not as good as expected, but this was mainly due to the modifications that were later made to both the UNDEX and impact simulations after the initial equivalency had been determined. Once the simulations had been modified, the UNDEX response of the composite panel was closer to its impact response than was observed for the aluminum panel. Good correlation was found between the impact simulations and the precision impact tests once the hybrid distributed impactor was more explicitly modeled. This correlation between the precision impact tests results and the simulated results validated LS-DYNA3D for that impact event and range of response. Using the Blatz-Ko compressive foam for the bumper urethane material model provided the best results of the simple material models used. The correlation of the UNDEX simulations with the UNDEX test results was not as good as was present for the impact simulations, although the correlation was much better for the aluminum panel than for the composite panel. The plane wave approximation of the UNDEX pressure loading was not sufficiently close to the actual initial load on the structure. None of the simple material models used for the composite's embedded rubber layers generated a good correlation with the experimental results. A thorough visco-hyperelstic characterization of the urethane layers to more accurately model their behavior could be expected to improve the correlation. Additional work is required to refine the method and further develop its capabilities.

6.0 References

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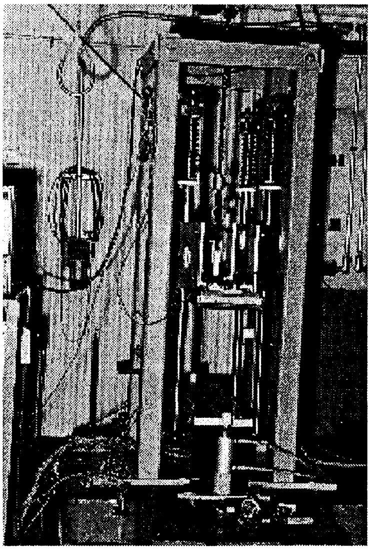

Figure 1: Test Structure and Aluminum Test Panel

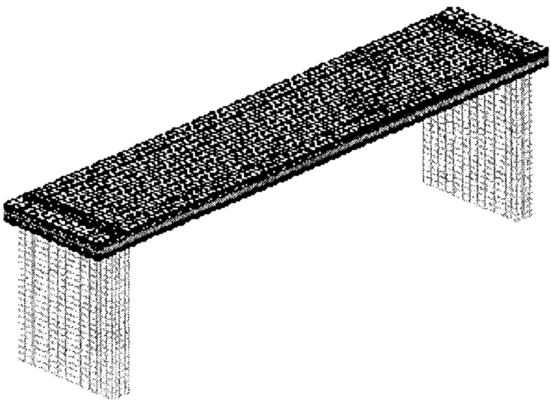

Figure 2: finite element mesh used for the structure

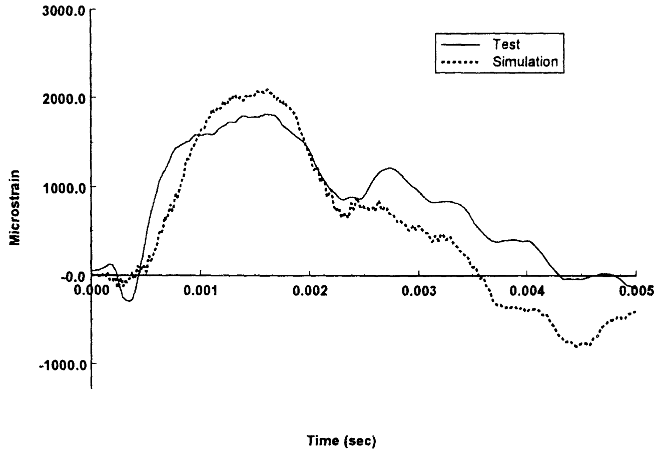

Figure 3: Test vs. Simulation Aluminum Impact Centerline Strain

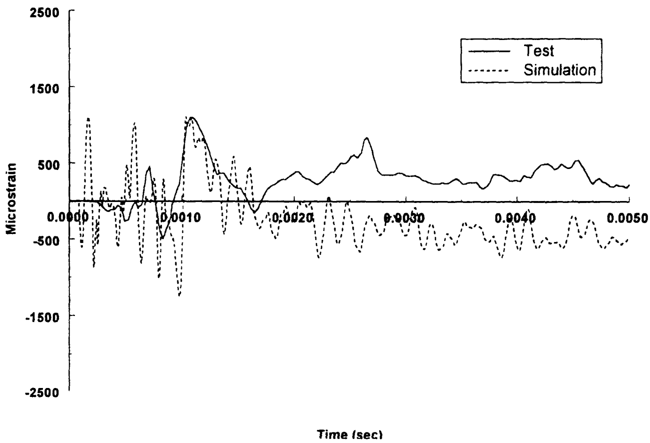

Figure 4: Test vs. Simulation Composite UNDEX Centerline Strain

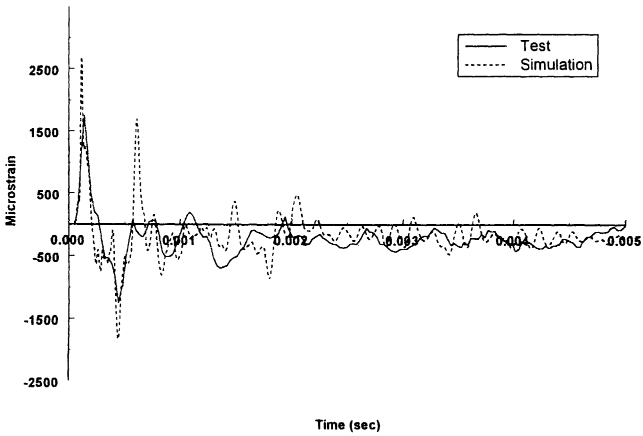

Figure 5: Test vs. Simulation Composite UNDEX Strain @ 11.5" Offset

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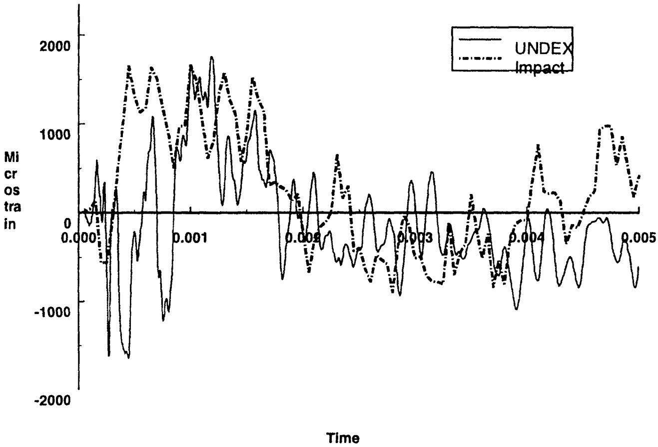

Figure 6: Initial UNDEX-impact strain comparison - Aluminum

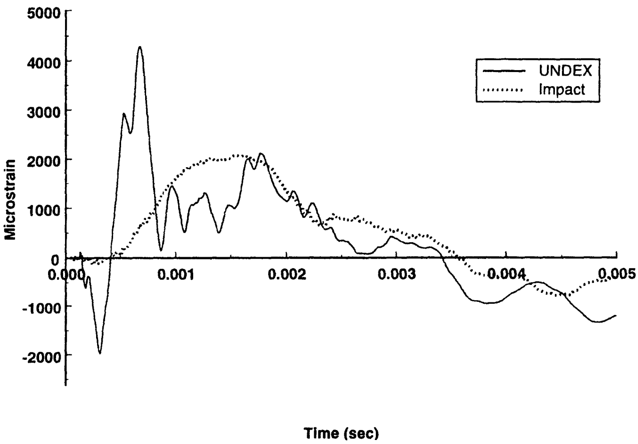

Figure 7: Final UNDEX-impact strain comparison - Aluminum

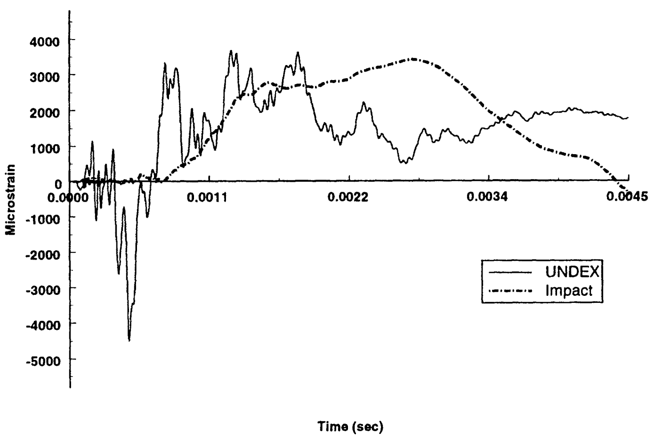

Figure 8: Final UNDEX-impact strain comparison - Composite Panel