LARGE DEFORMATION STUDIES ON STRUCTURES SUBJECTED TO UNDERWATER EXPLOSIONS

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by

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CERTIFICATE

This is to certify that the thesis titled "**Large Deformation Studies on Structures Subjected to Underwater Explosions**" being submitted by **Lt Cdr Pawan Kumar** to the Indian Institute of Technology, Delhi for the award of Degree of Doctor of Philosophy is a record of bonafide research work carried out by him. Lt Cdr Pawan Kumar has worked under our supervision and guidance and has fulfilled the requisites for the submission of this thesis which has reached the requisite standard for the Doctor of Philosophy Degree.

The results contained in this thesis have not been submitted in part or full, to any other university or institute for the award of any Degree or Diploma.

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ABSTRACT

The weapon and sensor inventory of modern naval forces has seen a very vast advancement in technology. The main aspect of interest is how well one can hide from the enemy and evades an attack and is also capable to launch an assault undetected. Hence, the main need of the hour is to develop hull which can withstand fair amount of shock transmitted from the modern weapons. The need to understand and study in detail the structural response of the hull to underwater explosive loads has become very important. With this motivation the present work has been able to ascertain the damage and failure patterns of simple panels which mimic the basic grillage structure which form the basic building blocks of the ship structure. Various parameters have been studied to bring out the behavior pattern in plates with variation in the shock factor, plate thickness, charge weight and standoff distances.

The failure of plates defining the rupture of plates post large deformations has also been studied and simulated for understanding the tearing pattern in plate panels. This becomes an important aspect for any marine structure as the water tight integrity is compromised when there is a failure in the structure. The water tight integrity is of paramount importance for the survivability of a marine structure such as a ship or a submarine. The study on plane plate panels yielded valuable results and observations very useful for design of ship/ air backed structures. A second category in the field of marine structures is the cylindrical structures; these are generally found in as an enclosing volume of a submarine or a caisson deep foundation for an oil rig. The safety of such

structures is also a concern which may be compromised intentionally or in the event of an unfortunate accident. The study on cylinders was conducted in phases firstly a numerical scheme modeling the underwater explosion in the fluid was carried out and the same was validated with available experimental results published in literature. This validated scheme and was used for further investigation on un-stiffened and ring stiffened cylinders. Literature review revealed that the in air explosions and the related studies were abundantly available in literature. The field of underwater explosion and the related studies are comparatively scarce. This work has been taken up in an endeavor to contribute to the field of study on underwater explosions. The power of validated numerical techniques is a very powerful tool to undertake underwater explosion studies as on the contrarily conducting underwater explosion experiments are a highly costly affair and are hazardous in nature to both the explosive handling and also to marine flora and fauna when tested in open waters.

Response of un-stiffened and stiffened rectangular flat air-backed plates subjected to UNDEX loads

A 3D finite element analysis was carried out on quarter plate models of WELDOX 460E. The shock factor was varied gradually by increasing the charge mass (W) and standoff distance (R) in steps. It was observed that the central deformation of the plate increased with the increase of the shock factor. All the cases studied numerically incorporated Johnson-Cook (J-C) stress-strain relationships and failure criterion. The parametric study involved variation of the charge mass, standoff distances, shock factors, W/R ratio and the plate thickness. The underwater explosion loading was applied as a pressure force on the wet surface of the air backed plate with fluid-structure interaction being incorporated to follow Taylor's plate theory. The boundary condition on the plate has been kept same as the one used in the experiments. The edges of the plates has been clamped and the numerical computation domain of the plate has been kept to a quarter model taking advantage in symmetry of loading, boundary condition and the geometry of the plate, leading to smaller model size and computation times.

The numerical procedure was first validated with UNDEX experimental results on 4mm thick high-strength (HS) plates available in literature and the same are presented Fig 3.2. Shock factors used in these experiments were 0.212, 0.300 and 0.424 which correspond to 10, 20 and 30 gm of PEK (Plastic explosive) respectively, and were placed at 0.15 m distance from the centre of the plate in a fresh water shock tank. The numerical analysis was performed with the same charge weights and standoff distances to achieve a validated numerical method for further parametric study. FE mesh size optimization was done and 10 elements per edge mesh density were adopted for analysis. The analysis for validation was conducted with metal plasticity definitions of Cowper-Symonds and Johnson-Cook plasticity formulations. The Johnson-Cook formulation was found to match with experiments closely and the same was used in further study.

Further numerical analysis was conducted on WELDOX 460 E un-stiffened plates of thicknesses 2, 4, 6, 8, 10 and 12 mm. 21 shock factors, varying from 0.3 – 1.74 were employed to study effect of change in charge mass and the standoff distance on the failure behavior of the plate. The central deformation Vs shock factors were plotted in all the cases studied and was found that the plate when reaching Mode I failure viz. large deformation was vibrating at the peak point after Mode I failure was achieved.

The mode II failure was defined earlier as, tearing of plate at the centre of the supports and progressively moving to the corners at the clamped edges. This phenomenon has been numerically simulated and discussed in this section; the tearing phenomenon is brought about by Johnson-Cook failure criterion. An FE scheme was adopted for calculating the equivalent plastic strain at the element integration points and computing the resulting damage parameter, Ω. A progressive damage feature is then adopted to delete the elements which attain the damage parameter Ω=1 symbolizing the damage/tearing of the plate at that element. This procedure is continued till the transient decay of the UNDEX load is completed, tracing the damage process in the plate. The mesh density near the plate edges was increased to capture the failure pattern.

The full plate model was adopted to study the nature of failure for a non-contact high energy underwater blast. The tearing pattern was seen to start at the plate edge rather than the plate centre nearest to which the explosive charge was placed, confirming to mode II failure. This is because even though the applied non-contact UNDEX load is non-uniform but is continuous and decays both spatially and transiently in the water domain. Hence, this blast phase is pseudo-uniform when the blast effects are considered. Further analysis was hence concluded with quarter plate model for saving computation time.

With establishing the mode II failure (Tearing at centre of supports) it was interesting to study the tearing pattern along the depth of the plate material at the centre of supports. Hence, the model was further refined at the supports to obtain 4 elements along the edge. The response of the model was computed for 1 ms time period of loading. The plate was clamped on two outer edges and symmetric boundary conditions applied on the remaining edges.

The study was further extended to stiffened plate of dimensions 0.25m x 0.3m with depth of stiffener, 0.01m. Stiffeners were placed in a uniform rectangular configuration with spacing of 0.1m to form a grillage structure, this configuration of stiffeners are usually found in marine structures which form the secondary load bearing members, which transfer the loads to primary members. In an event of an underwater explosion the grillage is the first structure which comes in contact with the shock pulse. The stiffened plate configuration had stiffeners of depth 0.1m with same shell thickness as that of the plate. In the event of an underwater explosion impulse applied to the flat surface of the plate-stiffener configuration, the effective span for the plate deformation is limited to the area between the stiffeners. Hence, as the area in this case is reduced as compared to the un-stiffened configuration. This would result in a reduction in the deformation of the stiffened plate. The extra strength added to the plate is due to the stiffness of the stiffeners which are resisting the impulse load in their in-plane direction. The observed deformation of an un-stiffened 2mm plate at 1.0 SF was 0.2 m and that with a stiffened configuration at the same shock factor was found to be 0.15 m. A comparative study was carried out to ascertain the advantage of stiffeners in comparison to a simple plane plate on plate grillage when subjected to underwater shock loads. It was necessary to maintain both the comparative models with similar mass per unit area for effective comparison. An un-stiffened plate of dimension 0.5x0.5 m with thickness of 4mm and a stiffened plate of dimension 0.5x0.5m with plate thickness of 3mm and stiffeners 0.5x0.021x0.004 m (6nos) were arranged.

The assumed plate density in both the above configurations was 7850 Kg/m3 the total calculated mass of the un-stiffened plate of dimension 0.5x0.5x0.004 m was 7.85 kilograms. Similarly the mass of the stiffened plate of dimensions 0.5x0.5x0.003 m and with 6 stiffeners of dimension 0.5x0.021x0.004 m was 7.86 kilograms. With similar masses of both the configuration comparative study was conducted on optimized mesh densities for both the analysis. The deformation trends comparison for both cases have been studied in detail and discussions with reasons were derived for the obtained deformation profiles.

Response of un-stiffened and stiffened submerged cylinders subjected to UNDEX loads

Previous sections have discussed in detail the dynamic response of plates in stiffened and un-stiffened configurations. The present study will concentrate on the cylinders subjected to UNDEX loads. Spheres form the best configurations for underwater vessels as this geometry is most stable under hydrostatic pressures underwater. The spherical structures lack critical space required for underwater vessels hence the tear drop shape suffices both the need of space and a hydrodynamic body for least hydrodynamic resistance. The cylinders form the central portion of the teardrop shaped vessels where critical space is available for crew and machinery. The study of effects and responses on cylindrical underwater vessels is of prime importance and will aid the design of such platforms. The study has been taken up in a phased manner with validation of numerical procedures to match experimental results and then to perform parametric study.

The numerical study was firstly validated to published experimental work with a 5gm TNT placed at 300 mm standoff distance, the validation results can been seen in Fig 6.7 and Fig 6.8. The pressure vs. time plot from experiments can be seen in Fig 6.3. The maximum peak pressure was found to be 17.2 MPa. The study involves three charge quantities placed at 1.04m standoff distance with variation of the shell thickness of the cylinder in both stiffened and un-stiffened configurations. The various configurations adopted in the parametric study were 1 kg TNT at 1.04m, 2kg at 1.04m and 5kg at 1.04m. The cylinder in the study was submerged in water and as the applied load was transient in nature and was applied at the source node in the fluid domain hence, the distribution spatially was calculated as per the fluid dynamics by calculation of the pressures in the fluid elements. The total wave formulation was used in the analysis option as they are more analogous to the structural loading and this formulation is relevant when the non-linearity in the fluid domain is necessary to incorporate the effects of fluid cavitation in the analysis.

The loading and boundary conditions in the present numerical analysis were given at most care as these have a good bearing in altering the results of the analysis. The test cylinder is submerged in water, which forms the acoustic domain. The applied UNDEX pressure load was located at the designated standoff distance inside the defined acoustic domain. The test cylinder submerged in water formed the acoustic domain. The applied pressure load was located at the designated standoff distance inside this domain. To improve the computational efficiency the mesh size adopted near the cylinder was smaller and it was gradually made coarser away from the cylinder as shown in Fig 6.4 and Fig 6.5.

The response modes of cylindrical structures to transverse loading has been studied and the accordion, whipping and the breathing modes. The three defined modes of responses of plates have been compared for all the above mentioned cases of variation in shock factor, shell thickness and standoff distances. Displacement profiles of the cylinder was extracted with all the cases in the study and the Mode I failure was established, which is large central deformation or dishing. A comparison of the deformation profiles of ring-stiffened vis-à-vis un-stiffened cylinders have also been brought out in the discussions. Some possible conclusions on the obtained deformation profiles are also discussed in the chapter.

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