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Computational analysis of blast loaded composite cylinders

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ABSTRACT

Explosion-resistant containers and chambers show promise for the safe storage and disposal of explosive materials and munitions. Light-weight explosion proof vessels, that are made of fiber-reinforced composite materials, are of specific interest, as their decreased mass allows for an ease in transportation. When developing fiber-reinforced composite structures for dynamic loading, efficient and reliable computational analysis techniques are required. The objectives of this study deal with developing a computational methodology that can be implemented when designing blast loaded composite structures. Specifically, efficient analysis procedures to predict large scale deformation and composite failure in dynamically loaded composite structures are developed for use with LSTC's LS-DYNA. In the process of developing the modeling methodology, a survey of the blast modeling methods available within LS-DYNA is completed and a recommendation is made considering both accuracy and computational cost. The developed methods are then used to simulate the blast loading and response of small, hollow composite cylinders, and the measured results of instrumented explosive tests are used for model validation.

1. Introduction

Explosion-resistant containers and chambers are a viable option for the safe storage and disposal of unwanted explosive materials. Light-weight explosion proof vessels, that are manufactured from fiber-reinforced composite materials, show specific potential. These containers offer a manageable size, mass, and transportability which allow for their use in several modern applications, including the safe transportation of explosives, as well as the discharge of large scale explosives, as a safer alternative to open air detonation. Regardless of the specific application, there is a need for safe and convenient methods of explosives disposal and light-weight explosion proof vessels are capable of fulfilling this need. Coupled with this requirement for safe methods for the disposal of unwanted explosives is a need for efficient analysis techniques that can be applied when designing dynamically loaded composite structures, such as light-weight explosion proof vessels. This study addresses this need and attempts to develop a computational methodology to be implemented in the process of developing blast loaded composite structures.

Significant research related to the development of explosion-resistant containers has been completed by the Russian Nuclear Federal Center and Sandia National Laboratories [1]. In their presented work, conclusions were specifically drawn regarding preferred materials for the blast application. Particularly, filament wound composite structures are preferred to steel when undergoing explosive loading. Unlike steel assemblies, composite structures, when loaded explosively, exhibit a threshold-free failure, and dangerous fragmentation is usually absent. Furthermore, of the numerous reinforcing fibers currently available for use, it was determined that glass fibers, when under pulse loading, have a suitably high load bearing capacity and energy absorption capability. Also, it was observed that when cylindrical shells of composite were subjected to centrally-placed, explosive charges, the shell structures would fail prematurely at strain levels significantly less than the limiting strain for the material. This behavior was explained by the axially-symmetric oscillations that the structures would undergo as a result of the pulse loading. To diminish this effect and to increase the overall structural strength, thin layers of steel were placed under the composite layer. The steel layers were observed to have a damping effect, as they tended to deform plastically under the internal pulse loading, thus increasing the overall load-carrying capacity of the structures.

Next, as it was intended that commercially available analysis codes be used to develop the computational methods, recent research related to the application of existing analysis software to simulations of dynamically loaded composite structures was reviewed. The examined references drew conclusions regarding both suitable analysis code packages, as well as the composite failure criteria best suited to the simulation of progressive composite damage and failure. Of the many explicit finite element commercial software packages discussed, LS-DYNA was often recommended. Similarly, of the numerous composite failure criteria currently implemented into the various simulation

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codes, the Chang-Chang failure criteria was often favorably discussed, due to the model's ability to differentiate between fiber and matrix failure types in the tensile and compressive directions. These model delineations result in the targeted reduction of the composite's moduli and allow for the simulation of progressive composite failure, in which the simulated composite material's elastic region is followed by an approximation of material softening due to a progressive loss of the composite's stiffness. This post-elastic response is particularly important, as simpler material models, in which the simulated elastic region is followed by abrupt, catastrophic failure, may not correctly account for the strain energy absorbed by the simulated structure. The reviewed references have shown that LS-DYNA, when combined with the Chang-Chang composite failure criteria, has successfully simulated such behaviors as the barely visible damage (matrix cracking and fiber breakage) in impacted composite plates [2], the response of impact absorbers composed of composite sandwich panels [3], the response of curved, laminated composite structures under low-velocity impact [4], the damage progression through a multi-functional composite armor [5], the ballistic impact response of composite helmet materials [6], and the damage response of a composite pressure vessel subjected to high-velocity impact [7].

1.1. Objectives

The objectives of this study deal with developing efficient computational analysis techniques that can be applied when designing blast loaded composite structures, such as explosion-resistant containers. The review of literature has indicated that finite element analysis tools should be capable of capturing and accurately predicting the large scale deformation behavior and progressive failure in explosively loaded composite structures. Therefore, in an effort to develop suitable numerical methods, two primary objectives have been defined. First, several of the reviewed references indicate that finite element analysis tools, such as LS-DYNA, can be used to predict progressive failure in dynamically loaded composite structures. Therefore, efficient analysis techniques will be developed following the referenced recommendations. Specifically, LS-DYNA and the Chang-Chang progressive composite failure criteria will be used to predict the failure and deformation of blast loaded composite structures. As there are multiple options for the simulation of explosive blasts available within LS-DYNA, ranging from the CONWEP blast approximation to a complete arbitrary Lagrangian–Eulerian approach, a survey of these methods will be completed in the interest of determining a modeling approach that is both computationally accurate and cost effective. Second, finite element models simulating the explosive testing of composite cylinders will be created. These simulations will model cylinders composed of an outer composite layer, with or without an inner liner of steel, undergoing centrally-placed, explosive charges, and experimental results from instrumented explosive tests will be used for model validation.

2. Finite element methods

Techniques for accurate and reliable composite failure prediction are necessary when developing high performance composite structures. Experimentally validated numerical methods are important when designing dynamically loaded structures, such as explosion-resistant containers, due to the high costs associated with the physical prototyping and explosive testing of composite parts. The references discussed in the previous section demonstrated the usefulness of commercially available, explicit solvers in simulating the behavior of dynamically loaded composite structures. Therefore, LSTC's LS-DYNA was used to develop a modeling technique capable of accurately predicting the deformations observed during the blast loading of composite structures with particular emphasis on computational efficiency.

2.1. General modeling approach

2.1.1. Shell element formulation

Four-noded shell elements were used exclusively in meshing all structural components. Although these elements are two dimensional, they are capable of taking bending stresses into account, and both in-plane and normal loads are permitted. The default LS-DYNA shell element formulation, Belytschko–Lin–Tsay, was applied in all cases due to its computational efficiency [8].

As compared to the more computationally expensive three-dimensional element, the Belytschko–Lin–Tsay two-dimensional element is not equipped for through-the-thickness stress calculations. Furthermore, the presence of through-the-thickness stresses could initiate and promote interlaminar delamination in laminated composite structures. However, these shortcomings were readily overcome. First, the wall thicknesses of the composite structures being modeled are small. This observation allows for thin-walled structure assumptions and stresses can be assumed as uniform across the thickness. Additionally, with regards to the accurate prediction of interlaminar delamination, the established finite element methods model failure within the adhesive bond between individual composite plies with contact definitions. Specifically, the individual composite plies are modeled separately and the characteristics for delamination are defined between adjacent plies with appropriate contact algorithms (see Section 2.1.3).

2.1.2. Material models

Dynamically loaded composite structures, such as light-weight explosion-resistant containers, generally consist of both metallic and fiber-reinforced composite components. Therefore, methods for simulating the behavior of isotropic metallic materials and orthotropic fiber-reinforced composite materials with LS-DYNA were determined.

2.1.2.1. Metallic material model. All metallic materials were modeled with LS-DYNA material model 3 (MAT 3). MAT 3, which correspond to the keyword command *MAT_PLASTIC_KINEMATIC, represents a bi-linear elastic-plastic material model that is capable of capturing the kinematic hardening plasticity of isotropic materials, as well as predicting isotropic material failure. Prior to failure, MAT 3 models the behavior of a metallic material with an approximated bi-linear stress-strain curve. The first linear portion of the curve represents the elastic region and is defined by the yield strength and the elastic modulus. While the second linear portion of the curve represents the plastic region and is defined by the tangent modulus of elasticity. A material modeled with MAT 3 will deform according to the bi-linear stress-strain relationship until the predicted strain exceeds a failure limit. When this failure limit, which is defined as the final elongation for metallic materials, is surpassed, elements are deleted from the model [8].

2.1.2.2. Composite material model. The composite materials were simulated with LS-DYNA material model 54 (MAT 54). MAT 54, or *MAT_ENHANCED_COMPOSITE_DAMAGE, is appropriate for synthesizing arbitrary orthotropic materials, such as the unidirectional layers in a laminated composite structure, and is capable of predicting failure within a dynamically loaded composite structure with the Chang-Chang failure criteria [8]. As discussed by [9], when a composite material experiences failure, there will be some degree of property loss in the vicinity of the damaged area. Furthermore, the magnitude and severity of the property loss is dependent upon the initial mechanism of failure. Specifically, according to the Chang-Chang criteria, if the initial failure is due to matrix cracking, the transverse direction properties of a unidirectional composite shall be reduced to zero, but the longitudinal, or fiber, direction properties and the shear stress-strain relationships shall remain unchanged. Alternatively, if the initial failure is within the