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Explicit phantom paired shell element approach for crack branching and impact damage prediction of aluminum structures

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ABSTRACT

The main objective of this paper is to exploit an efficient and a simplified extended finite element shell formulation for prediction of ductile fracture and crack branching of thin-walled aluminum structures subjected to impact loading. In order to characterize an arbitrary crack initiation, propagation and brunching, a phantom paired shell element approach is further developed and implemented into Abaqus' explicit solver via its user defined element (VUEL). The energy dissipation due to failure is captured by a cohesive force along the crack interface when its accumulative plastic strain reaches a critical value. A numerical technique for modeling out-of-plane crack branching phenomena is also developed by activating the phantom nodes and re-grouping the element connectivity. Four numerical examples are used to demonstrate the applicability and accuracy of the extended shell element approach for ductile failure prediction of an indentation test, a multi-bay stiffened panel with crack branching, an explosively loaded plate, and a cylinder subjected to impulsive loading.

1. Introduction

The use of aluminum alloys and their extruded structural components in advanced vehicle construction has a great advantage in minimizing a vessel's weight. Given its one-third density of steel and 70% of the tensile strength of steel, the resulting weight of aluminum high speed vehicle is much lower than a similar vessel constructed from steel. The reduction of structural weight allows for increased payload, top speed, and operation range at lower operational and total ownership cost. Since a vehicle is an operation-critical structure, it must be designed to have a sufficient level of residual strength both during and after an extreme loading event such as impact. The extreme dynamic loading can seriously damage the vessel form by dishing and holing the stiffened panel. To ensure the sufficient strength and damage tolerance of a structural component, a full-scale analysis coupled with experimentation has to be implemented during the design iteration, structural certification, and shock qualification process.

Design of large, high-speed aluminum vessels operating in a hostile environment requires the welded structure to withstand sub-critical growth of manufacturing flaws and service-induced defects against failure under extreme dynamic loading. The compounding effects from material heterogeneity and reduced strength in Heat Affect Zone (HAZ) makes the welded aluminum structure prone to crack initiation under normal operating conditions. In the presence of unexpected extreme loading events, these initial flaws will propagate, branch, and be arrested by the nearby stiffeners. The complexity in component geometry, material heterogeneity, and 3D stress distribution, will likely make crack growth curvilinear, turning towards the stiffener. Failure to account for the 3D crack growth geometry may lead to poor predictions of the crack tip driving force which will have a pronounced impact on the fracture pattern and its resulting load-deflection prediction.

Typical size of a stiffened panel used in a large vehicle structure is about 10 m × 10 m with a thickness of 0.013 m. For such thin-walled structures, the computational effort using solid finite elements is prohibitive if a good element aspect ratio is maintained. Structural shell elements are widely used in such applications because they offer the advantage of allowing the use of large elements while maintaining adequate numerical accuracy. Typical shell elements have an in-plane size of 2–30 times larger than the plate

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thickness. It is therefore highly desirable to develop an efficient fracture analysis and design tool to characterize crack growth simulation in a large scale thin-walled structure within an efficient shell element formulation.

When the crack path is unknown a priori, a pioneering approach based on cohesive elements embedded at all element boundaries is developed by Ref. [23] and the method had been improved by Ref. [6] by introducing cohesive elements only along element boundaries where a certain fracture criterion is met. Given the pre-defined element topology, the crack growth direction is expected to be mesh dependent in addition to the added artificial compliance in the model resulting from the finite cohesive stiffness used.

In order to characterize an arbitrary crack initiation and propagation, the extended finite element method (XFEM) coupled with shell kinematics was developed by Ref. [2] based on the Mindlin-Reissner theory and an enhanced assumed strain formulation to alleviate locking in thin shells. Instead of using the approach of nodal enrichment via additional degrees of freedom, an alternative approach based on two overlapping elements has been developed by Ref. [11] where their identical kinematical representation to XFEM has been proved by Ref. [20]. A phantom paired approach coupled with a cohesive injection has been developed by Ref. [21] and implemented for the Belytschko-Tsay (B-T) shell element [27]. To further enhance the computational efficiency, a one-point integration scheme along with element-wise progression of the crack is implemented by Ref. [21] for the simulation of dynamic cracks in thin shells and its applications to quasi brittle fracture problems. Note that the partition of unity enriched methods for static and dynamic fracture in thin shell analysis have been also developed by Refs. [7,15–18] besides from the alternative methods for fracture in thin shells by Refs. [3] and [1]. A 7-parameter, 6-node triangular solid-shell element in conjunction with a rate-dependent cohesive zone model has been developed by Ref. [13] and enhanced by [26] by implementing an explicit time stepping scheme, the Johnson Cook phenomenological model, and a shifted cohesive zone model. However, the implementation of these XFEM methodologies for shell elements is still within a standalone finite element code with limited capabilities in terms of element library, material constitutive models, contact algorithms, and graphic user interface for finite element model generation and display of analysis results.

Driven by the strong needs from commercial industries and DoD Labs in the application of commercial finite element software such as Abaqus for the design and certification of large scale thin-walled metallic structures, it is imperative to implement the XFEM for shell elements within a commercial finite element software. A great challenge exists since a commercial finite element software such as Abaqus has placed a restriction in altering the number of elements and their connectivity. The presence of multiple cracks and their growths in different planes will make the kinematic description of these cracks challenging within an XFEM framework for Abaqus. A novel approach for characterization of multiple crack initiations and propagations has to be developed via the phantom nodes re-grouping and re-assignment of element connectivity.

The present paper is divided into five sections. In Section 2, the development of phantom paired Belytschko-Tsay (B-T) shell [27] is presented for Abaqus along with its numerical implementation. Section 3 describes the modeling approach for crack branching along with its capability demonstration. Section 4 gives the description of a material model and a crack initial and propagation criterion. The final demonstration is reported in Section 5, in which four examples are selected for the ductile failure simulation of an indentation test, a multi-bay stiffened panel with crack branching, an explosively loaded square plate, and a cylinder subjected to impulsive loading.

2. Phantom paired Belytschko-Tsay (B-T) shell for Abaqus

2.1. Overview of a B-T shell

The B-T shell is based on a combined co-rotational and velocity strain formulation. The co-rotational portion of the formulation avoids the complexities by embedding a coordinate system in the element. The selection of velocity-strain or rate-of-deformation in the B-T shell formulation makes the conjugate stress the same as the physical Cauchy stress that can greatly facilitate the constitutive description.

The velocity field of the shell is given by

$$\mathbf{V}(\xi,t)=\mathbf{V}^{mid}(\xi,t)-\varsigma\mathbf{e}_3\times\boldsymbol{\theta}^{mid}(\xi,t) \tag{1}$$

where $\mathbf{v}^{mid}\in R^3$ are the velocities of the shell mid-surface, $\boldsymbol{\theta}^{mid}\in R^3$ are angular velocities of the normal to the mid-surface, ς is the pseudo thickness which varies linearly from $-h/2$ to $h/2$ along the shell thickness h, and $\xi=(\xi_1,\xi_2)$ are material coordinates of the manifold that describes the mid-surface of the shell. The nomenclature used in Eq. (1) is illustrated in Fig. 1.

A kinematic theory based on corotational rate-of-deformation and corotational Cauchy stress rate is used. The corotational coordinate system serves as a local coordinate system to measure the rate-of-deformation of elements during the simulations as shown in Fig. 2.

Using Eq. (1), the velocity components of an arbitrary point with thickness-direction coordinate can be defined as

$$\begin{aligned} v_x &= v_x^{mid}+\theta_y^{mid}\varsigma,\\ v_y &= v_y^{mid}-\theta_x^{mid}\varsigma,\\ v_z &= v_z^{mid} \end{aligned} \tag{2}$$

Define the corotational components of the velocity strain d by

$$d=\frac{1}{2}\left(\frac{\partial v_i}{\partial v_j}+\frac{\partial v_j}{\partial v_i}\right) \tag{3}$$

After substituting Eq. (2-3) into Eq. (2-2), we have

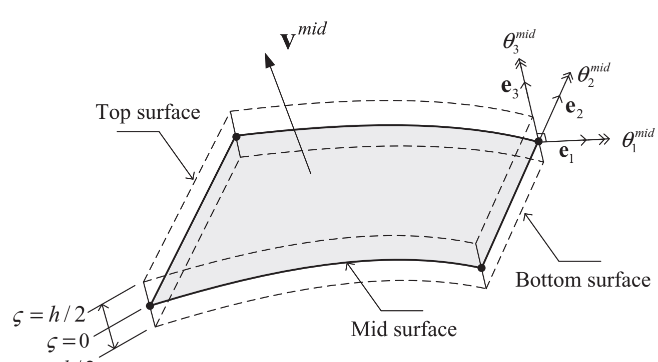

Fig. 1. A geometric description of Belytschko-Tsay shell.