COVER SHEET

Title: **Reduction in Computational Cost of Progressive Failure Analysis of Composite Structures**

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ABSTRACT

Designing aircraft structures requires efficient modeling approaches to iterate on multiple structural configurations to achieve an optimal design. Typically, damage tolerance is not considered at the design stage because of the high computational cost in its implementation within a finite element modeling approach. Therefore, analytical or empirical approaches are often used to size critical damage-tolerant structures once an optimal design is determined. In this study, the Progressive Release eXplicit Virtual Crack-Closure Technique (PRX-VCCT) is assessed for its capability to cost-effectively evaluate skin-stringer separation of a blade-stiffened panel that is subjected to seven-point bend loads. An initial verification study was performed to evaluate PRX-VCCT to accurately simulate skin-stringer separation with respect to existing cohesive element approaches. Furthermore, the influence of element size, ranging from 0.10 in. to 0.40 in., on the total computational time using the PRX-VCCT is investigated. The results indicate that the PRX-VCCT can be used to accurately simulate skin-stringer separation using large element lengths (0.40 in.). Additionally, a significant reduction in the computational time to simulate skin-stringer separation is observed using the PRX-VCCT. Large-scale progressive damage analysis using PRX-VCCT can be implemented early in the design cycle of composite structures without requiring a global-to-local modeling approach.

INTRODUCTION

High-fidelity computational modeling of progressive damage in composites is necessary to reduce reliance on testing. However, the computational cost and time associated with these modeling approaches are significantly increased compared to traditional strength analyses. Two-dimensional finite element analysis is typically used to efficiently size composite structures in conjunction with lamina failure criteria such as Tsai-Wu or Tsai-Hill. These failure criteria are phenomenological models that efficiently describe the failure of composites at a macroscale [1]. Hence, the failure of

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composite laminates depend on in-plane and ply-level longitudinal, transverse, and shear stresses that are estimated using classical lamination theory. Such methods are only applicable to simulate the onset of in-plane ply failure and do not consider all composite failure mechanisms.

Significant progress has been made in developing methodologies to simulate composite constituent (fiber and matrix) failure and delamination between plies [2]. Damage tolerance certification requirements are usually satisfied by using empirical or analytical approaches to quantify the amount of damage in a composite part at a structural length scale [3]. High-fidelity computational modeling of progressive damage at structural length scales is an excellent approach to verify these empirical or analytical methods, but it is very impractical to design with these approaches because of the high computational time. To reduce the computational time, a global-to-local approach [4] is often used to assess the damage that is located in critical regions within a composite part. Although global-to-local approaches require additional user time to set up the finite element model (FEM), the overall benefit of increased damage resolution outweighs the added computational time.

Of all the failure mechanisms, delamination has received the most attention because it can occur at relatively low out-of-plane loads as compared to other failure mechanisms. Two primary strategies are used to simulate delamination between plies in a composite: a cohesive zone model (CZM) approach [5] and a virtual crack-closure technique (VCCT) [6]. Using a CZM approach, small cohesive element sizes (<0.01 in.) are necessary to estimate the fracture process zones during delamination because of the low matrix ductility typically observed in aerospace-grade composites. As a result, the computational time to complete a simulation is high because of a large number of elements and degrees of freedom are needed. Therefore, computationally-efficient FEMs or surrogate modeling approaches [7] are necessary to predict damage in composites used in structural applications.

Recently, benchmark studies [8] have shown that the Progressive Release eXplicit Virtual Crack-Closure Technique (PRX-VCCT) can be used with element sizes (~0.08 in.) that are notably greater than element sizes needed for CZMs (~0.02 in.). The traditional VCCT is a linear elastic fracture mechanics approach that is used to estimate the strain energy release rate (SERR) of a cracked body based on nodal forces and opening displacements that are located near the crack tip [6]. A separate strategy is required to model delamination growth using VCCT. One option is to release the nodal pairs along a delamination plane once the SERR reaches a critical value (fracture toughness) and assume that the crack tip immediately transitions to adjacent nodal pairs. This strategy can result in erroneous predictions for any case other than a quasi-static two-dimensional crack [9]. In addition, progressively larger errors can occur if the mesh coarsens using the VCCT. Alternatively, a re-meshing scheme can be used to obtain an intermediate crack length between previously adjacent nodal pairs [10]. However, this technique has not gained traction in modelling of delamination because of the difficulty to robustly deploy when multiple delamination planes are near each other. Kinematic constraints are used in the PRX-VCCT to represent intermediate crack positions via the progressive release of nodal pairs at the crack tip once the assumed fracture criteria are achieved [9]. Therefore, intermediate crack positions can be determined between nodal pairs based on the stiffness of the kinematic constraint without requiring remeshing. The kinematic constraint is prescribed by assuming a linear spring stiffness between nodal pairs [9]. Crack propagation is estimated explicitly based on the critical SERRs and an assumed growth rate (both in static and fatigue). As a result, a crack propagation strategy that is not constrained by convergence issues that are associated with predicting crack growth can be achieved using the PRX-VCCT [11].

The National Aeronautics and Space Administration (NASA) recently initiated the Hi-Rate Composite Aircraft Manufacturing (HiCAM) project to evaluate composite manufacturing methods to reduce production time. In particular, through-thickness stitching has been shown to simplify the composite assembly process and impede delamination growth. In previous work [12], the performance of the stitches to impede delamination growth in a stitched blade-stiffened panel was evaluated using a CZM approach. An explicit solver within the Abaqus* finite element software was determined to be necessary to reach solution convergence and consistent load-displacement behavior to previous analyses [12]. The total computational time ranged from 10 hours to 18 hours depending on the number of processors (16 to 29 processors) used, which is considered impractical in a design setting.

In this study, finite element modeling of a stitched blade-stiffened panel subjected to seven-point bend (SPB) loads is performed using the PRX-VCCT. An illustration of the stitched SPB test is shown in Figure 1. The SPB test is used to simulate skin-stringer separation of a stiffened panel subjected to in-plane compression and in a post-buckled configuration [13]. Out-of-plane displacements are constrained at the bottom supports, whereas a downward displacement is applied with the top indenters to induce skin-stringer separation. Two finite element models are considered, an initial simplified FEM and a full-scale FEM of a blade-stiffened panel. The simplified FEM was performed to verify the PRX-VCCT with existing CZM approaches. The full-scale FEM was performed to evaluate the computational benefits of using the PRX-VCCT. In the following section, the accuracy of the PRX-VCCT method to predict the load-displacement and crack growth behavior is discussed along with some limitations. Afterward, the influence of select element sizes using PRX-VCCT is investigated with respect to the total computational time and previous analysis [12]. The accuracy of the PRX-VCCT method to predict skin-stringer separation and its potential computational cost benefits are discussed.

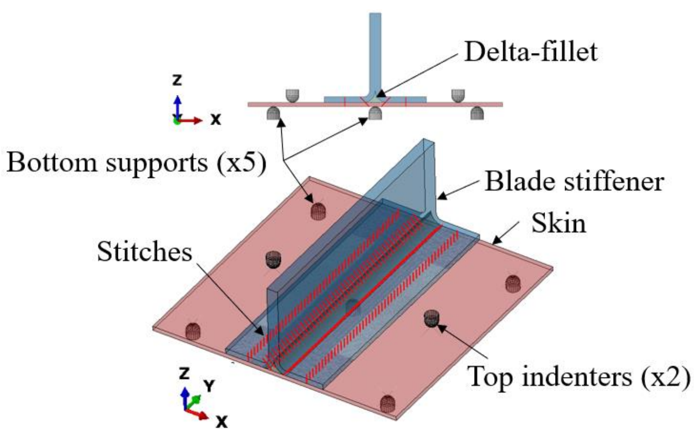

Figure 1. Illustration of an SPB test.

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VERIFICATION OF PRX-VCCT AND ITS LIMITATIONS

An initial, simplified SPB FEM was used to verify and demonstrate the efficacy of the PRX-VCCT. In the current analysis and the following full-scale analysis, the PRX-VCCT was implemented with Abaqus/Standard using user-defined elements (UELs) that are deployed at the skin-stringer interface. Two additional CZMs are independently used to compare to the PRX-VCCT: the Abaqus commercial cohesive element and an in-house cohesive element called Pligcoe [14]. The Abaqus commercial CZM was performed using Abaqus/Explicit commercial software based on previous analysis [12], whereas Pligcoe CZM was implemented using Abaqus/Standard implicit analysis. Semi-automatic mass scaling was used with the explicit approach with a time period of 0.5 seconds. A stable time increment of 5×10^{-7} seconds was used to minimize the kinetic energy in the explicit analysis model.

The simplified SPB model, shown in Figure 2, is a quarter model of the full SPB model to reduce the high computational time observed using the Abaqus/Standard implicit static analyses with cohesive elements. In this simplified SPB model, the blade of the stiffener is neglected; however, the flanges of the blade-stiffener that interface the skin are included. Three elements are used in the through-the-thickness direction for both the skin and flange of the blade stiffener. The skin and stiffened flanges are modeled with a uniform element size of 0.01 in. A unidirectional layup configuration is assumed. The zero-degree direction is assumed to be along the X-axis. The material and fracture properties used in this analysis are shown in Tables I and II, respectively [12]. Linear elastic material behavior is assumed in the skin and the flanges of the blade-stiffener and no other damage mechanisms are incorporated.

Within this current implementation of the PRX-VCCT, a uniform mesh with orthogonal mesh lines is required and used in the present analysis. Additionally, an initial crack is required when using the PRX-VCCT to simulate skin-stringer separation. The initial crack is specified by setting the damage index of the first row of elements along the length of the flange to one (Figure 2), which results in an initial crack length of 0.01 in. Damage is assumed to only grow in a self-similar fashion in the x-y plane. A mixed-mode Benzeggagh-Kenane (B-K) fracture criterion was used to simulate the mixed-mode delamination behavior at the skin-to-stringer interface.

TABLE I. LAMINA PROPERTIES FOR THE SKIN, STIFFENER, AND DELTA-FILLET [12].

Region	**Longitudinal Tensile Modulus, E_1 (psi)**	**Transverse Tensile Modulus, E_2=E_3 (psi)**	**Poisson's Ratio $\nu_{12} = \nu_{13} = \nu_{23}$**	**Longitudinal Shear Modulus, $G_{12} = G_{13}$ (psi)**	**Transverse Shear Modulus, G_{23} (psi)**
Skin	2.13E+07	1.26E+06	0.320	7.49E+05	4.35E+05
Stiffener	2.13E+07	1.26E+06	0.320	7.49E+05	4.32E+05
Delta-Fillet	9.36E+06	9.51E+06	0.046	7.20E+05	4.32E+05

TABLE II. FRACTURE PROPERTIES FOR THE FLANGE-TO-SKIN INTERFACE [12].

Region	Mode I Penalty Stiffness, K_I (lbf/in.^{3})	Mode II Penalty Stiffness K_{II} (lbf/in.^{3})	Mode I Fracture Toughness, G_{IC} (lbf/in.)	Mode II Fracture Toughness, G_{IIC} (lbf/in.)	Elastic Tensile Strength, σ_C (lbf/in.^{2})	Elastic Shear Strength, τ_C (lbf/in.^{2})	B-K Exponent, η_{BK}
Flange-to-Skin Interface	1.80E+08	1.3E+08	1.370	4.22	9.04E+03	1.35E+04	2.07

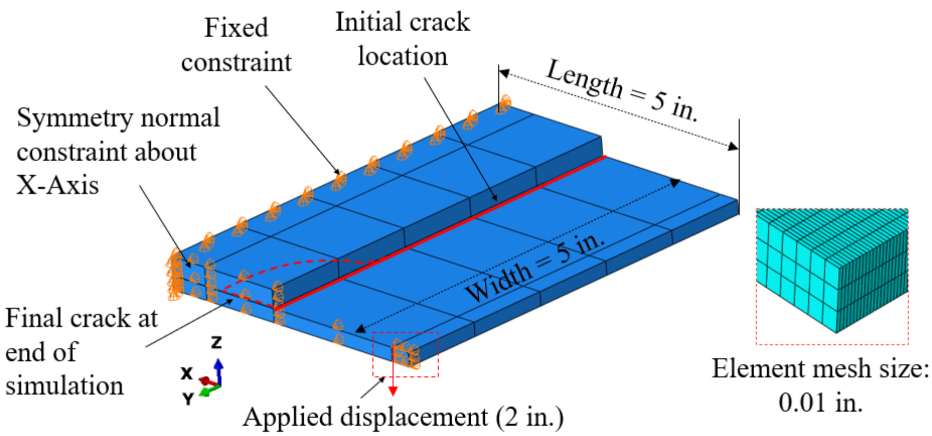

Figure 2. Simplified SPB model.

The reacted load as a function of the applied displacement for select interface elements (PRX-VCCT, Pligcoe, and Abaqus) is shown in Figure 3. Initially, a linear load-displacement response is observed until delamination begins to initiate. After delamination initiates, the slope decreases and is followed by a linear increase in load until a maximum displacement of 2 in. is achieved. A good correlation is obtained between the PRX-VCCT, Pligcoe, and Abaqus solutions. At an applied displacement of 2 in., the maximum load of the Plicoe solution is underpredicted by PRX-VCCT by approximately 2%. The differences between each solution are initially observed at the onset of delamination, where a slightly greater load is predicted by the Abaqus and Plicoe CZMs than the PRX-VCCT model. In Figure 4, the delamination shape at an applied displacement of 2 in. is shown for the PRX-VCCT model and Abaqus CZM. A semi-circular delamination shape is observed, which is consistent with previously performed analyses [12,15]. For additional clarity, the final crack shape is also superimposed in Figure 2. Additionally, good agreement of the skin-stringer delamination shapes is obtained between each solution with respect to the predicted crack position along the flange's edge (within 2%). The crack growth that is estimated using an Abaqus CZM is slightly underpredicted by the crack growth predicted using the PRX-VCCT. This behavior is associated with the development of a fracture process zone ahead of the crack tip to promote steady-state delamination when using a cohesive element formulation, which is not considered when using a VCCT.

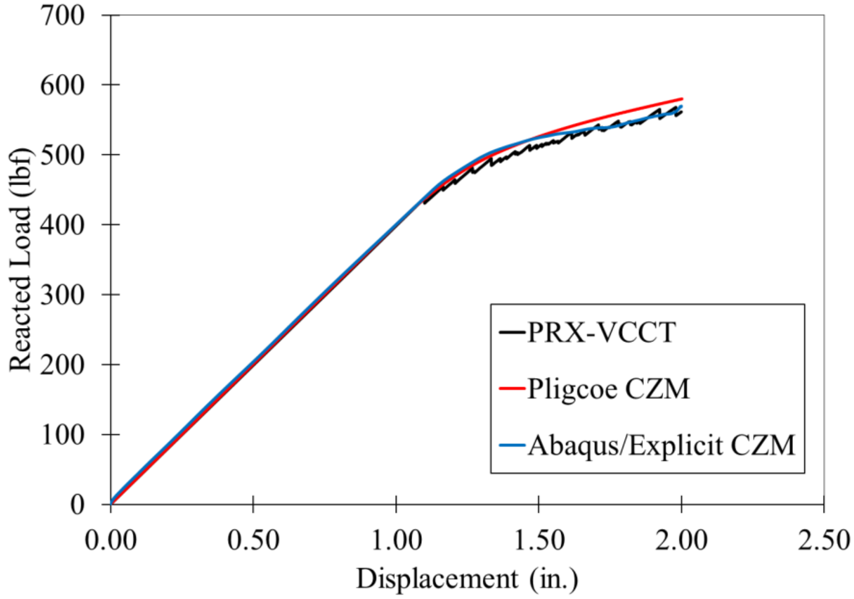

Figure 3. Reacted load as a function of the applied displacement.

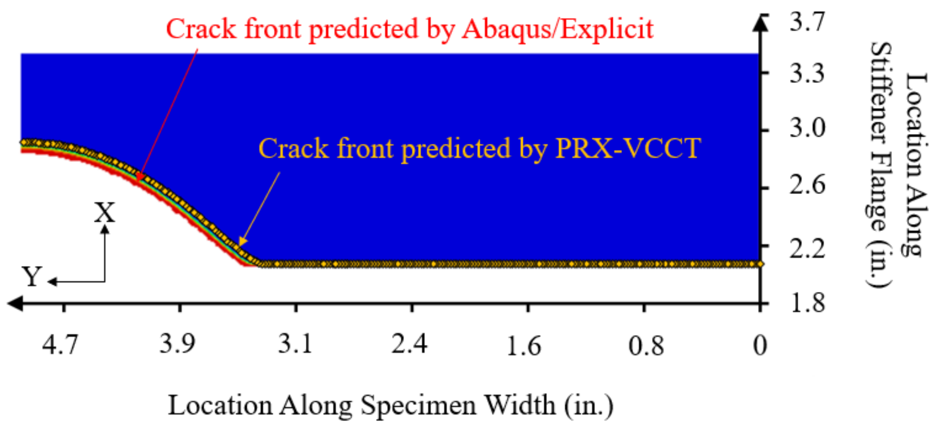

Figure 4. Delamination shape at an applied displacement of 2 in. for the PRX-VCCT approach cohesive element approaches.

IMPLEMENTATION OF PRX-VCCT FOR STRUCTURAL APPLICATIONS AND ITS COST BENEFITS

The PRX-VCCT was implemented on a previously-created FEM [12] that was used to simulate a stitched blade-stiffened composite panel subjected to SPB displacements. A full-scale SPB model is used to illustrate the cost-effectiveness of the PRX-VCCT and is shown in Figure 5. The skin and stiffener flange sections were modeled as continuum shell elements with reduced integration (SC8R) with a layup configuration of $[\pm 45^{o}/(0^{o})_{2}/90^{o}/(0^{o})_{2}/\mp 45^{o}]_{3}$ and $[\pm 45^{o}/(0^{o})_{2}/90^{o}/(0^{o})_{2}/\mp 45^{o}]_{4}$, respectively. The 0^{o} plies are oriented along the Y-axis (along the length of the blade stiffener). The delta-fillet underneath the blade region was modeled using hexahedron continuum elements with reduced integration, C3D8R. The bottom supports and top indenters were represented as analytically rigid surfaces. Frictional contact was imposed between the skin and indenters, and a frictional coefficient of 0.33 was assumed. Translational displacements were constrained at the bottom supports, whereas a 0.5 in. displacement in the negative Z direction was applied to the skin with the top indenters to induce skin-stringer separation. Linear elastic material behavior was assumed in the skin, stiffener, and delta-fillet regions. Similar to the simplified SPB model, only damage associated with separation between the skin and stringer was modeled.

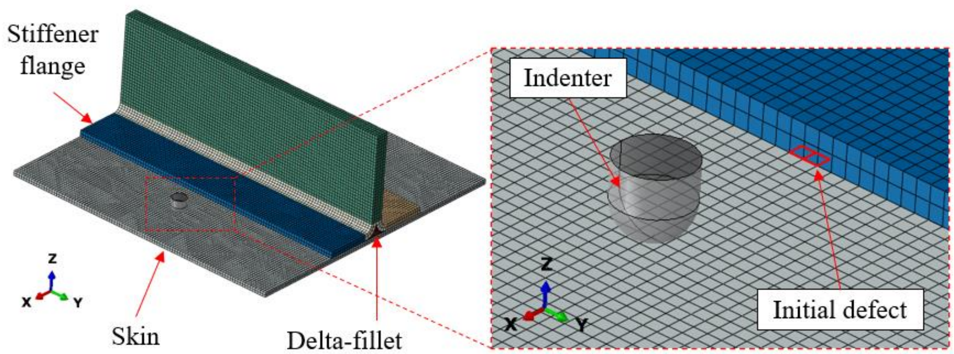

Figure 5. Full SPB model.

The reacted load as a function of the applied displacement for the blade-stiffened panel that is subjected to SPB displacements is shown in Figure 6. The influence of select element lengths (0.10, 0.20, 0.30, and 0.40 in.) on the load-displacement response was evaluated with respect to a baseline Abaqus/Explicit CZM with a minimum element length of 0.01 in. For all cases, an initial linear load-displacement behavior is observed. For relatively coarse meshes (0.20–0.40 in.), a slight increase in the initial slope is observed and is attributed to the large elements not approximating the elemental stress gradients during loading. The accuracy of the load-displacement response does not appear to be dictated by how accurately the FEM can predict skin-stringer separation using the PRX-VCCT. The accuracy of the load-displacement response appears to be more influenced by the number of elements needed to predict the elastic response of a blade-stiffened panel when subjected to representative structural loads.

Upon initial delamination, a decrease in the load-displacement slope is observed and is followed by a steady-state skin-stringer separation. Increasing the element length from 0.10 in. to 0.40 in. decreases the initial load at which skin-stringer separation occurs. This behavior is attributed to an increase in the initial crack length because the PRX-VCCT method requires an orthogonal uniform mesh with equal element lengths in front and behind the initial crack. In this FEM, the initial crack is also assumed to be located at the two foremost elements in front of the indenters (Figure 5); therefore, increasing the element size also increases the initial crack length. This behavior may be alleviated by artificially extending the flange of the stiffener to prevent the large element sizes from affecting the solution, assuming the extended flange does not influence the load-displacement response of the stiffened panel. Lastly, the skin-stringer separation front for two mesh densities (0.1 and 0.4 in.) is shown in Figure 7. The delamination front shapes and lengths at an applied displacement of 0.1 in. are equivalent for both element lengths in Figure 7. Decreasing the element size is also observed to decrease the resolution of the delamination front using the PRX-VCCT method.

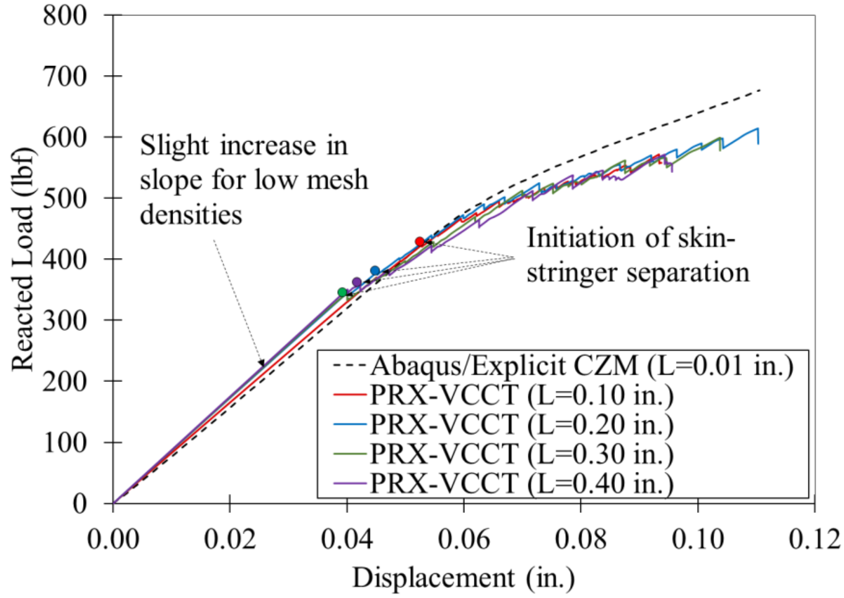

Figure 6. Load-displacement behavior for select element sizes (0.10 in. to 0.40 in.) and analysis types (Abaqus/Explicit and PRX-VCCT).

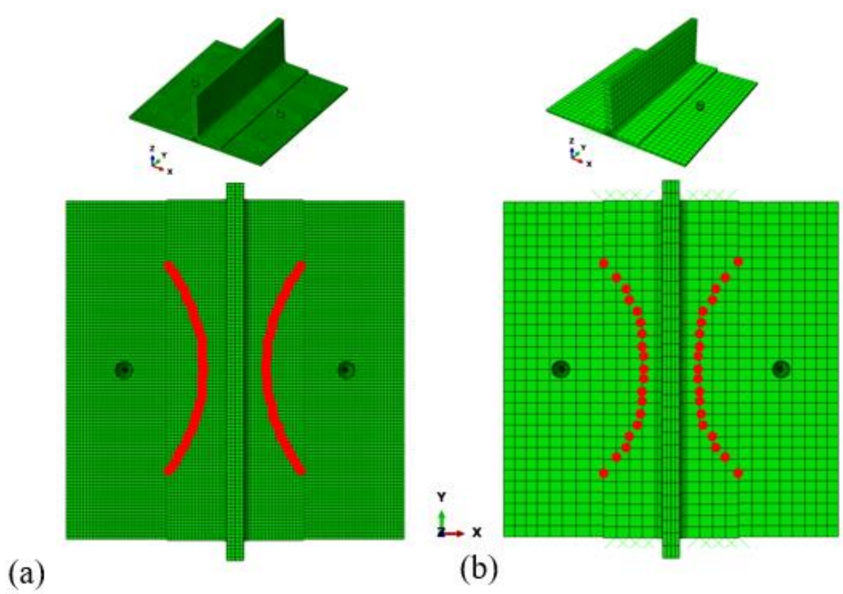

Figure 7. A comparison of skin-stringer separation fronts for select element sizes, (a) Length = 0.1 in. and (b) Length = 0.4 in.

The computational time of SPB analyses performed using the PRX-VCCT is shown in Table III for select element sizes (from 0.08 in. to 0.40 in.) and compared to previously performed explicit analyses using a cohesive zone approach [12]. A 97% improvement in the computational time is observed when the element length is increased from 0.02 in. to 0.40 in using the PRX-VCCT with respect to the CZM approach. This improvement is primarily because the total number of elements is also greatly reduced; thus, decreasing the total number of degrees of freedom needed to iteratively solve the solution. The total number of elements needed by the cohesive zone approach is approximately 600,000 as compared to the approximately 6000 needed by the PRX-VCCT. Based on this observation, the PRX-VCCT may yield an approach that enables insight from a damage tolerance perspective without requiring a global-to-local approach. Furthermore, this approach may be used early in the design cycle without the significant cost of increased mesh refinement and numerical model size in the sizing of aerospace structures.

TABLE III. COMPUTATIONAL TIME FOR SELECT ELEMENT SIZES.

Element Size (in.)	Approach	Solver	No. of Cpus	Computational Time (hr)	Number of Elements	Percent Difference (%)
0.02	Cohesive	Abaqus/Explicit	17	13.55	595567	-
0.08	PRX	Abaqus/Standard	15	5.23	76180	61.40
0.10	PRX	Abaqus/Standard	15	2.2	45607	83.76
0.20	PRX	Abaqus/Standard	15	0.82	13807	93.95
0.30	PRX	Abaqus/Standard	15	0.52	6367	96.16
0.40	PRX	Abaqus/Standard	15	0.45	5647	96.68

CONCLUSIONS

In this study, blade-stiffened panels subjected to SPB displacements are investigated using the PRX-VCCT. Select element sizes (0.02 in. to 0.40 in.) were investigated with respect to the computational time and compared to previously performed explicit analyses. Additionally, an initial verification was performed to show the efficacy of the PRX-VCCT to predict the load-displacement and skin-stringer separation behaviors by comparing PRX-VCCT to existing cohesive element methods. A good correlation (within 2%) was observed in the load-displacement and skin-stringer separation responses between PRX-VCCT and existing CZMs. By increasing the element length from 0.02 in. to 0.40 in., a substantial decrease in the computational time was observed. The PRX-VCCT approach is computationally efficient and effective in predicting skin-stringer separation of large-scale structures without requiring a global-to-local modeling approach.

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