MODELING HAIL IMPACT DAMAGE AND RESIDUAL STRENGTH IN COMPOSITE STRUCTURES

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Abstract

The fiber-reinforced composite materials have been used increasingly for primary structures in commercial aircrafts due to their high strength to weight ratio, fatigue resistance and corrosion prevention capabilities. Composite structures on aircrafts are subject to dynamic loading such as hail impacts that can severely degrade material properties of the structures and lead to their mechanical failure. It is important to evaluate the performance of composite structures involved in such events for a reliable design. A computational model based on peridynamic theory has been under development for impact resistance and damage tolerance analysis of composite structures, and has proved to be a promising method for addressing analysis challenges. In peridynamic theory, the presence of discontinuities in a deforming structure does not limit its applicability. In this paper, we present our work on modeling hail impact damage and residual strength of composite panels, and compare our simulation results with the experimental ones.

1 Introduction

The usage of fiber-reinforced composite materials for primary structures in commercial aircrafts has increased due to their high strength to weight ratio, fatigue resistance and corrosion prevention capabilities, and the ability of being manufactured into a large unitized structure. The layered nature of composite laminates affords engineers greater flexibility in design and optimization of aircraft structures. Composite structures in service are subject to dynamic loading such as hail impacts that can severely degrade the material properties of the structures and lead to their mechanical failure. It is important to numerically evaluate the performance of composite structures involved in such events for a reliable and optimal design. A computational model based on peridynamic theory is proposed to analyze the effects of hail impacts and the residual strengths in composite structures.

Many experimental and theoretical studies have been conducted to characterize the impact resistance and tolerance of composite structures. As early as in 1970s, the dynamic behaviors of composite materials were studied in [1, 2]. Thereafter the assessments of impact damage in composite structures have been pursued by many researchers [3-7]. Impact damage on sandwich plates was presented in [8, 9]. The effects of stiffeners in composite panels on impact damage and compression after impact (CAI) strengths were considered in [10-12]. Based on different theories, many composite damage and failure models have been proposed. They include models based on linear elastic fracture mechanics, cohesive elements, and element-failure algorithms, etc. The interaction between intra-ply matrix cracking and inter-ply delamination was taken into consideration in [13, 14]. Besides the influence of different stacking sequences where fiber and matrix properties are kept constant, the effects of different fiber materials, which are of interest for increasing damage resistance, were investigated in [15, 16]. In [17], the impactor was modeled as a disintegrable ice ball, which is representative of hailstones, for impact problems on composite plates. These damage models are typically implemented in a finite element analysis code. The modeling method proposed in this paper is based on the peridynamic theory which is fundamentally different as it does not rely on finite element codes to solve the underlying partial differential equations. It does not require an extra treatment for discontinuities.

2 The Peridynamic Theory

The peridynamic theory reformulates the basic equations of motion in such a form that the internal forces are evaluated using an integral formulation rather than through partial derivatives of a stress tensor field [18, 19]. So the presence of discontinuities in a deforming structure does not limit its applicability. The equation of motion in the peridynamic theory is

$$\rho \ddot{\mathbf{u}}(\mathbf{x},t) = \int_R \mathbf{f}(\mathbf{u}(\mathbf{x}',t) - \mathbf{u}(\mathbf{x},t), \mathbf{x}'-\mathbf{x})\, dV_{\mathbf{x}'} + \mathbf{b}(\mathbf{x},t) \qquad (1)$$

where ρ is the material density, **u** is the displacement vector, R is a neighborhood of **x**, and **f** is a pair-wise function whose value is the force vector (per unit volume squared) that the particle **x'** exerts on the particle **x**. The physical interaction between **x'** and **x** is referred to as a bond. The bond force depends only on its length and orientation in the reference configuration and the relative displacements at the ends of the bond. It is reasonable to assume that material particles separated by a distance greater than some fixed value do not interact. This distance is called the horizon of the peridynamic model. Each particle interacts directly with a number of nearby particles within its horizon through interactive bond forces. Material damage is introduced at the bond level with bond breakages, and is treated consistently throughout the deformation process, regardless of whether a discontinuity or a crack is present.

The peridynamic theory has been under development and used for damage and failure analysis in composite structures, and has proved to be a promising method for addressing analysis challenges. In peridynamic model for composites, there are distinct intra-ply bonds in fiber and non-fiber directions and inter-ply bonds for inter-laminar interactions to take account of the anisotropic behaviors. The detailed peridynamic modeling schemes and the previous results on modeling damage and failure in composite structures have been presented in [20-22].

In [20], the peridynamic method has predicted damage propagation patterns and failure modes in large-notch composite coupons with different lay-ups and stacking sequences under tensile loads. The results have reproduced the experimentally observed dependence of the damage propagation direction on the relative percentage of fibers in different orientations. In [22], the failure modes and residual strengths of cruciform composite plates under more realistic biaxial loads are modeled using peridynamic theory. The simulation results agree fairly well with the experimental ones. The work done so far suggests a high level of confidence on the peridynamic modeling method for composite structures and provides great promises in more complicated applications.

3 Peridynamic Simulations

The peridynamic computational model for composite materials employs the peridynamic constitutive relations with distinct bonds for fibers and matrix of a specific lamina and inter-laminar bonds between plies [20]. Here the peridynamic model is used to evaluate impact damage in composite panels and determine their residual strengths through compression after impact (CAI) analysis. We present three cases, 1) a composite panel is impacted by a rigid impactor; 2) a composite panel is impacted by an in-flight hail impactor; and 3) four damaged composite panels are compressed after impact.

3.1 Impact by a Rigid Impactor

It is well known that fiber-reinforced composites are vulnerable to transverse impacts to such a degree that the resulted delamination and matrix damage can lead to significant reduction of the load-carrying capacity of the composite structures. First we present the results of a composite panel impacted by a rigid impactor to validate the peridynamic model.

The dimensions of the rectangular composite panel in Fig. 1 are 60.96 *cm* in length and 22.86 *cm* in width. The composite panel was manufactured from composite tapes of BMS 8-276, Grade 190, Form3. There are 10 plies in total, and both top and bottom plies are fabric plies. The zero degree fiber direction is along the longer panel dimension. The fiber orientation in each ply is in one of the four traditional angles, *i.e.* 0, 45, -45 or 90 degrees. During the impact test, the specimen is placed in a specially designed support fixture and subject to an impact of 84.74 *J* by a rigid spherical impactor of 6.10 *cm* in diameter. After the impact test, the panel was studied by nondestructive inspection technique to get the experimental data about delamination patterns and extents.

The comparison of total delamination areas between the simulation results and the experimental data, and the simulated delamination patterns ply by ply are shown in Fig. 1. The color dots in simulation results represent the material area with delamination damage. Please note that the simulation results and the NDI data use different color scheme to indicate delamination severity. It does not affect the comparison in total delamination area, which shows that the simulated damage area agrees well with the experimental data. In Fig. 1, the peridynamic simulation results also reveal the delamination patterns ply by ply, and the delamination region has distinguishable orientation between different plies because of the different fiber angles in adjacent plies. The delamination occurs in plies at the bottom half of panels. The distribution of delamination through thickness is illustrated in Fig. 2. The synthesis of color areas in NDI data obtained by inspections from both front and back sides of the panel indicates the delamination distribution through the thickness of the damaged composite panel. The simulation result in Fig. 2 reveals the same delamination distribution through panel thickness.

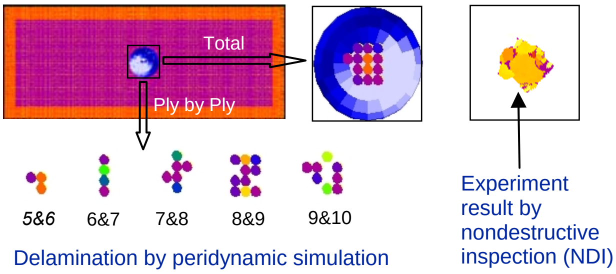

Fig. 1. Comparison of delamination area.

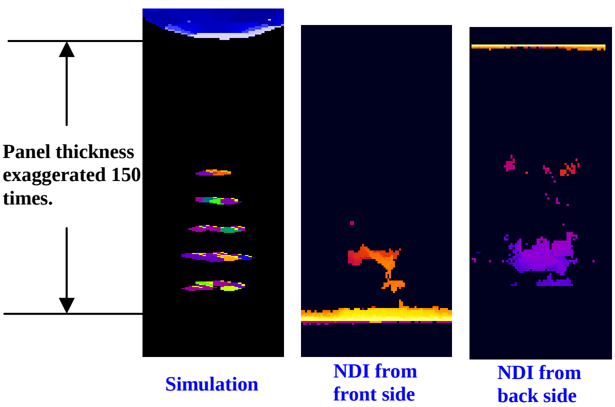

Fig. 2. Comparison of delamination distribution.

3.2 Impact by an In-flight Hail Impactor

Both in-flight and ground hail damage can remove aircrafts from service and result in excessive revenue loss for airliners. We present an example of a composite panel impacted by an in-flight hail projectile, and predict the delamination area and extent using the peridynamic model.

The composite material used is the same as the one in Section 3.1. There are 10 plies in total and both top and bottom plies are fabric plies. The fabric materials are not the same as those in Section 3.1. But they do not differ too much. The fiber orientation in each ply is in one of the four traditional angles, *i.e.* 0, 45, -45 or 90 degrees. The diameter of the spherical hail impactor is 6.10 *cm,* and its temperature at the time of impact is about 261 *K*. The impact energy is 177.41 *J* and the impact angle is 25 degrees.

The predicted delamination area and damage extent by peridynamic simulation are displayed in top two plots in Fig. 3. The color area on the left shows the damage and material removal area in a close-up view. The experimental result with similar setup conditions, as used in peridynamic simulation, is shown in the bottom plot in Fig. 3. The marked area is the measured delamination area, and there is also apparent material removal in the impact region. The results in Fig. 3 show that both the damage area and extent predicted by peridynamic model are correlated well with the experimental data.

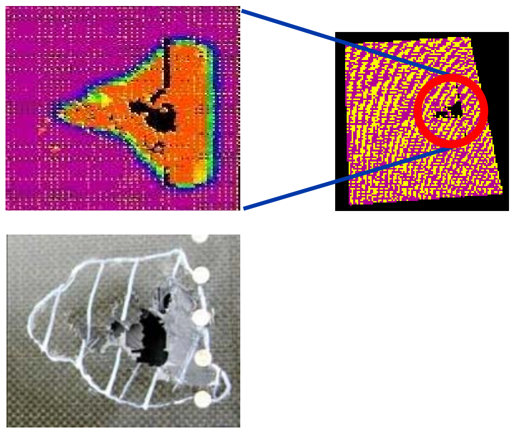

Fig. 3. The delamination area of a composite panel subject to in-flight hail impact.

3.3 Residual Strength after Impact

The CAI problem is considered to be one of the most important issues in the design of composite structures. The CAI tests are used to assess the residual strengths of the impacted composites structures. To limit the number of the expensive CAI tests for an efficient design, it is essential that CAI strengths can be determined by numerical simulations. In this section, we will show that the peridynamic modeling method is successful in simulating the CAI performance of composite panels with different lay-ups and stacking sequences.

The rectangular composite panels for CAI tests are 38.1 *cm* in length and 12.7 *cm* in width. There are 16 plies in total and both top and bottom plies are fabric plies. The 0 degree fiber direction is along the longer panel dimension. During the impact phase of the test, the panels are placed in a specially designed support fixture and subject to an impact by a spherical impactor of 2.54 *cm* in diameter with prescribed energy level ranging from 27.1 to 35.3 *J*. There are four different test panels with different lay-up and stacking sequences. After impact test, the panels are slightly trimmed with the damage location in the center for subsequent compression residual strength tests. During the compression phase of the test, the panels are placed in a specially designed stabilization fixture to prevent bucking, and are compressed until they fail. The peridynamic simulations are conducted continuously, with the induced damage state kept, from the impact phase to the compression phase. The comparison of the simulated CAI strengths with the experimental data is shown in Table 1. The values are normalized by an unspecified length scale. The simulation results by the peridynamic model have shown close agreements with the experimental data. The difference between the simulated CAI strengths and the experimental ones is within 5% for the panel with the highest fraction of 0 degree fibers in Panel A, and within 3% for all other panels.

Table 1. Comparison of CAI strengths predicted by simulations with those from experimental tests.

	Simulation	Experiment
Panel A	186.55	178.50
Panel B	167.70	170.00
Panel C	147.55	150.50
Panel D	129.65	130.00

3 Conclusions

For structural failure problems, the spontaneous discontinuities such as fracture and cracks emerge in the interior of the material as a result of deformation. The peridynamic theory incorporates damage, crack, and fracture as a natural component of material deformation process without any supplemental relations for the initiation and propagation of damage and cracks. A computational model based on the peridynamic theory has been under development for impact resistance and damage tolerance analysis of composite structures, and has proved to be a promising method for addressing analysis challenges. In this paper, we present our modeling and analysis work based peridynamic theory on predicting impact damage and residual performance of composite panels for three different cases. The predicted delamination area and extent by both rigid and hail projectiles and the predicted residual strengths by CAI are correlated fairly well with the experimental results. The simulation results demonstrate the capability of the peridynamic method for modeling and analyzing the damage and failure behaviors of composite structures.

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