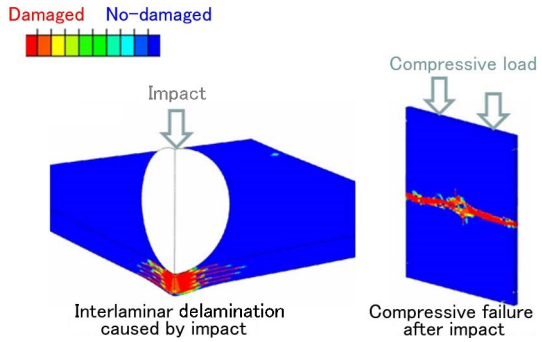
Strength Prediction Technology for Composite Materials Simulating Damage Phenomena



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This paper presents a strength prediction technology for composite materials using numerical analysis. Composite materials typified by fiber reinforced plastics (FRP) are superior to metals in specific strength, and are mainly applied to transportation equipment such as aircraft. However, the damage phenomena of FRP are complicated, and a large number of tests are required to ensure structural reliability, so the development period tends to be lengthy. Therefore, Mitsubishi Heavy Industries, Ltd. (MHI) is working on the development of an analytical technique to simulate complex damage phenomena of FRP and predict strength with high accuracy. This analytical technique expresses damage to the fiber, resin, and interlayer with numerical analysis and predicts strength by sequentially solving the progress of damage. This report introduces examples of the analysis of compressive strength reduction due to impact damage, which is particularly problematic for FRP.

1. Introduction

Composite materials, which are typified by fiber reinforced plastics (FRP), are superior in specific strength and have good fatigue properties and corrosion resistance, so application to structural materials has been progressing especially for transportation equipment such as aircraft, for which weight saving is effective. When a load is applied to an FRP, damage to the fiber, resin, interlayer, etc., occur in the laminated structure (0.1 mm order), which causes structural failure while interacting in a complicated manner. It is difficult to consider these complex damage phenomena theoretically and analytically, and strength prediction was difficult. Meanwhile, transportation equipment that heavily relies on composite materials requires high reliability, and a large number of tests are required to ensure reliability in product development. This is one reason for the longer development period. Therefore, it is desirable to build analytical techniques that can rationally predict a wide variety of structural strengths using a small number of basic test data items.

Therefore, we are working on the development of numerical analysis technology that can simulate damage to composite materials and predict the strength. This paper outlines this technology and explains the analysis examples.

2. Strength prediction technology

2.1 Lamination structure and damage phenomena of FRP

An FRP is mainly produced by stacking fiber sheets at various angles and solidifying them with a resin. When a load is applied to an FRP, breakage/kinking of the fiber and tensile/shear cracking of the resin occur in each laminated layer. In addition, interlaminar delamination occurs due to tensile and shear loads. These damage phenomena occur and progress while interacting with each other, leading to the final failure of the entire FRP. The initiation of damage can be predicted by the conventional strength evaluation based on simple stress and strain criteria, but it was not possible to take into account the behavior in which damage progresses while interacting with other damage phenomena, so it is difficult to predict the strength at the time of final failure.

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2.2 Damage phenomena analysis method

We developed an analytical method to represent damage in numerical analysis in order to predict the strength in consideration of damage phenomena interacting in a diverse and complicated manner with each other. This method uses a finite element model simulating the laminated structure of an FRP and adopts a material constitutive law considering damage for each layer and the interlayer.

Each layer was modeled as a normal shell element or solid element, and the influence of damage to the fiber and resin were considered for each layer. The initiation of damage was determined on the basis of a stress-based fracture criterion. As the fracture criterion, the LaRC criterion[2,3] proposed by NASA Langley Research Center was applied. The LaRC criterion is characterized by refining the evaluation formula of the fiber kinking phenomenon in the compressive stress field, which could not be evaluated accurately with the conventional fracture criterion. Progress in the damage is expressed by the deterioration of stiffness. An energy-based method, in which the stiffness is deteriorated in accordance with the progress of damage and the amount of energy dissipation of the element in a completely damaged state is equal to the fracture toughness of the material, was used. These damage initiation and progress criteria were formulated for each damage phenomenon of fiber and resin, and fiber failure and resin cracking were simulated. A special element called a cohesive element was inserted between the layers. The cohesive element defines the interfacial behavior using interfacial traction and relative displacement. Interlaminar delamination was simulated with respect to this interfacial behavior in consideration of damage initiation based on the stress criterion and damage progression based on the energy criterion. **Figure 1** shows a schematic diagram of this damage modeling. Damage initiates at the stage when the stress reaches the prescribed value for all damage in terms of fiber failure, resin cracking and interlaminar delamination, and the stiffness decreases with damage progression. The area of the triangle surrounded by the stress-strain relationship in the figure corresponds to the fracture toughness.

In this method, when damage occurs in an element, the redistribution of the stress is expressed by locally deteriorating the stiffness in the damaged element. Due to this stress redistribution, damage progresses to adjacent elements, and the load by which the load bearing capacity is ultimately lost is predicted.

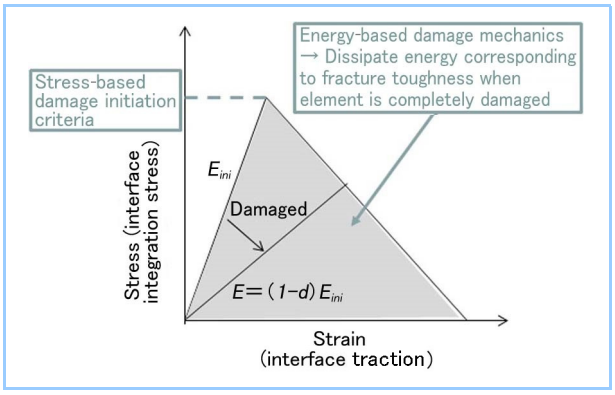

Figure 1 Material constitutive law considering damage
After the stress-based damage initiation criteria is satisfied, the behavior of energy-based damage progression (rigidity deterioration) is shown.

3. Analysis example

This section introduces an example case where strength prediction was performed by analyzing the occurrence of internal damage at the time of low-speed impact application and a strength test after the occurrence of impact damage. Such a test is unique to composite materials and its importance is recognized particularly in the aircraft field. If a weak impact such as that caused by the dropping of a tool is applied, no damage is found in appearance, but interlaminar delamination occurs internally in many cases. It is well known that when a compressive load is applied in this state, the strength greatly decreases compared with a case of no damage. This strength is called compression after impact (CAI) strength. Aircraft, etc., must be designed to have

appropriate strength even in the state of impact damage or other defects. CAI strength is one of the factors leading to an increase in the number of test items.

3.1 Comparative test

The test specimen was a 24-ply quasi-isotropic laminate produced by the VaRTM method using a high-strength type carbon fiber and epoxy resin used for aircraft and wind turbines. First, drop weight impacts with the impact energy of 20 J and 55 J were applied. **Figure 2** depicts the impact test apparatus. After applying the impact, a compression test of the same specimen was performed with the jig shown in **Figure 3**.

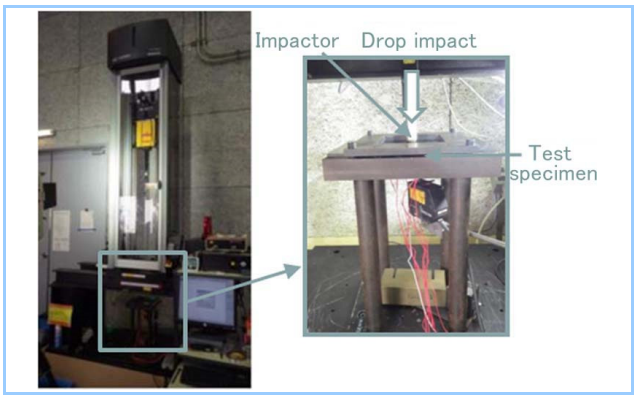

Figure 2 Impact test apparatus
The falling weight type test apparatus for application of impact.

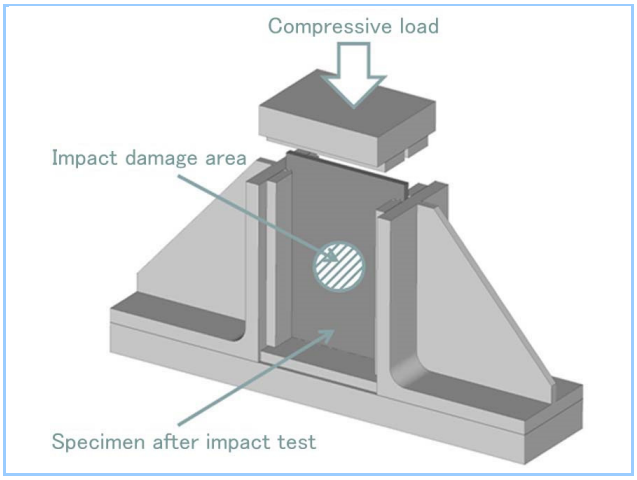

Figure 3 CAI test tool
The test tool for applying a compressive load to obtain the strength after impact damage.

3.2 Analysis procedure

As can be seen in **Figure 4**, analysis was carried out using a finite element mesh simulating the laminated structure according to the procedure and the boundary conditions presented in **Figure 5**. The analysis was performed constantly from damage occurrence caused as a result of the impact to compression failure to reproduce the test procedure.

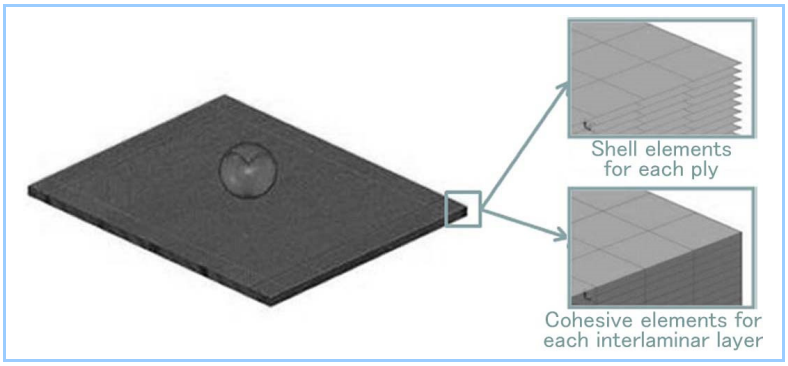

Figure 4 Finite element mesh
The mesh simulating the laminar structure of a composite material

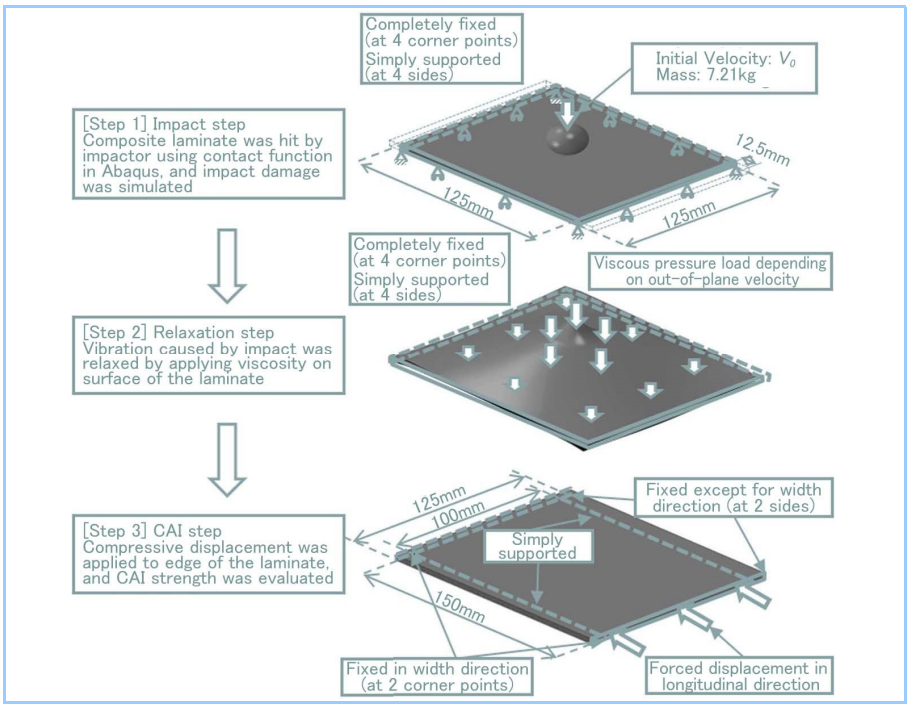

Figure 5 Analysis procedure and boundary conditions
Analyzing constantly from impact application to compression for reproduction of the test procedure

3.3 Comparison of test results and analysis results

Figure 6 compares the state of interlaminar delamination after impact application obtained by the impact analysis with the UT (ultrasonic testing) inspection image after the impact test. This is a projected figure obtained by superimposing damage for all layers. **Figure 7** compares the state of interlaminar delamination with the observation image in the reference.[4] Figure 6 and Figure 7 indicate that generally known delamination of a double helical structure occurred and the delamination shape seen in the test was obtained.

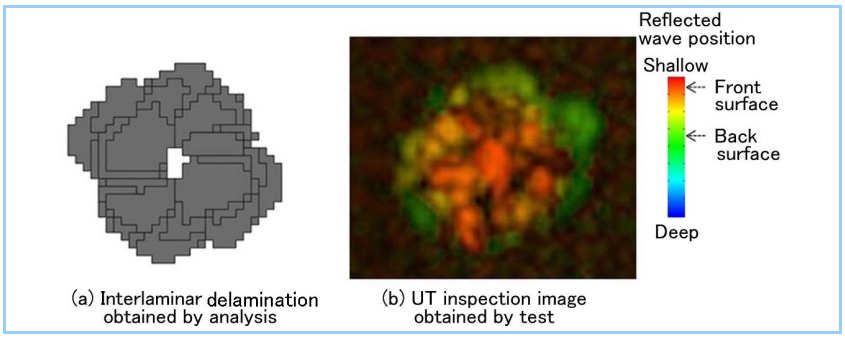

Figure 6 Interlaminar delamination caused by impact (projection)
The analyzed completely-damaged interlaminar element and UT inspection image from the test are shown as a projection.

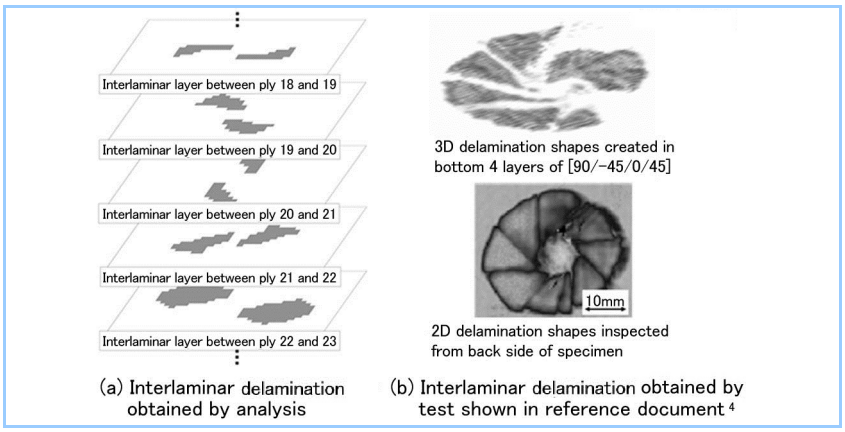

Figure 7 Interlaminar delamination caused by impact (each interlayer)
The analyzed completely-damaged interlaminar element and UT inspection image from the test are shown for each interlayer.

Figure 8 presents the relationship between the impact damage projected area and the impact energy. The area is of the delamination projection diagram (Figure 6) and normalized by the value of the test results of 55J. As can be seen in Figure 8, the damage area obtained by analysis displayed good agreement with the test results.

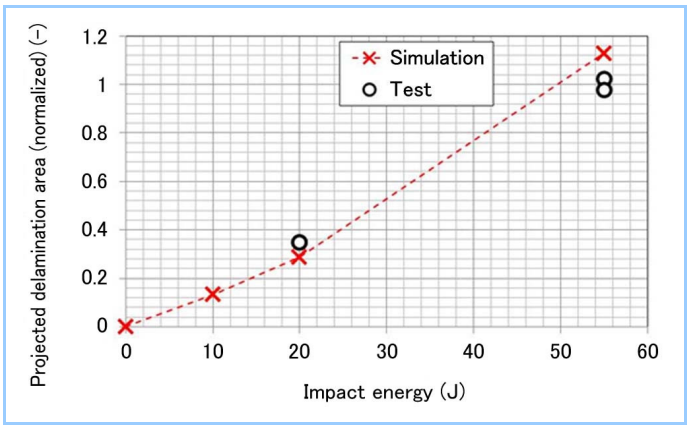

Figure 8 Relation between impact damage projection area and impact energy
The impact damage projection area was normalized with the area at 55 J impact in the test.

Figure 9 illustrates the progress of interlaminar delamination and fiber damage obtained by compression analysis. In the vicinity of the maximum load, the damage related to kinking of the fiber progressed in the width direction, indicating that the fracture mode was dominated by fiber kinking. This was a result caused by bending deformation of local buckling that occurred in the part that was damaged by the impact.

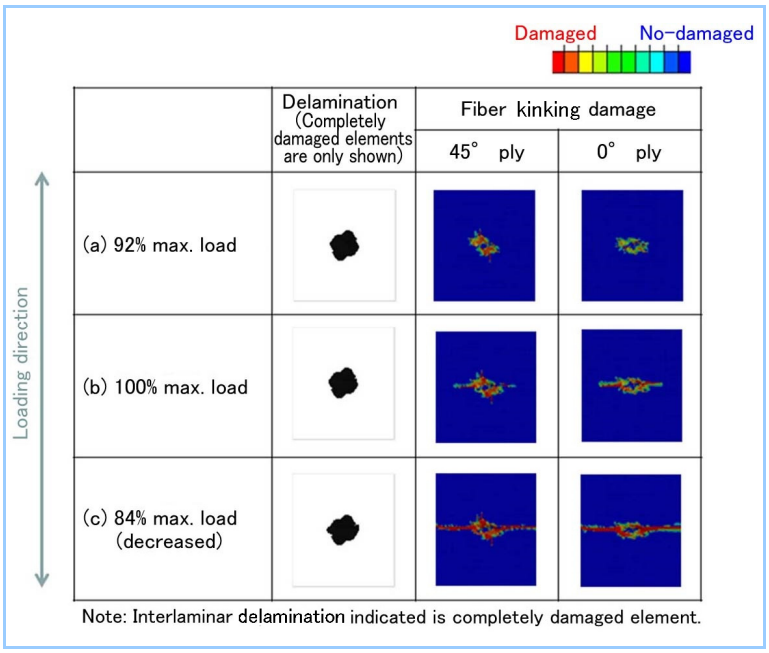

Figure 9 Progress of interlaminar delamination and fiber kinking obtained by compression analysis
In the vicinity of the maximum load, the damage related to the kinking of the fiber progressed in the width direction.

Figure 10 gives the relationship between the CAI strength and the impact energy. The CAI strength is normalized by the value of the test results of the undamaged material. In the test, the strength was lowered to about 50% as a result of the impact, compared with the non-damaged material. The strength prediction results using compression analysis showed good agreement with the test results.

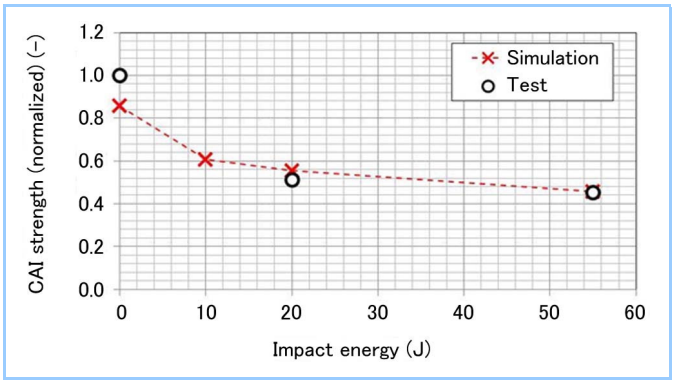

Figure 10 Relationship between CAI strength and impact energy
The CAI strength was normalized by the strength of the undamaged material in the test.

4. Conclusion

Numerical analysis technology that simulates the damage phenomena of FRP enabled strength prediction, which was difficult in the past. As a result of the analysis of damage occurrence at the time of impact, which is a problem peculiar to FRP, as well as CAI strength, it was confirmed that it is possible to predict the impact damage area and the CAI strength. This method is a versatile analysis method that can be applied to stress concentrating parts, manufacturing defect parts, etc., in addition to the examples introduced here. We plan to further improve the analysis to allow for consideration of environmental dependence and more comprehensive evaluation such as fatigue damage evaluation, etc., in the future.

References

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