New Indicator for Health Monitoring of Structures Made of Fiber-Reinforced Composite Materials Under Low Impact Loading

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Abstract: Structural health monitoring (SHM) is critical for the safe design and use of many societally essential structures, such as bridges, highway infrastructures, high-density buildings, and technologically critical applications in the aerospace and automotive industries. Among the many modes of mechanical loading, dynamic loading (such as vibration or impact) is perhaps the most crucial as it often leads to sudden failure of the structures. In addition, more structures – such as aircraft, spacecraft, and even automobiles – are currently built with composite materials due to their high specific strength and toughness (compared to metals). Although many SHM studies have been performed in structures made of fiber-reinforced composites, the response of structures, especially concerning high impact loading mode, may be different compared to metals is one example of such a unique damage mechanism in composites. We propose here new damage indicator based on the theory of strength of materials applied to plate geometry. The findings suggest that the new damage indicator is more sensitive towards detecting failure of the materials or structures, compared to the existing methodology.

Keywords: Structure Health Monitoring, Composite material, new damage indicator, Impact loading

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1. Introduction

Structural health monitoring (SHM) is critical for the safe design and use of many societally important structures, such as bridges, highway infrastructures, high-density buildings, as well as technologically important applications such as in aerospace and automotive industries. For developing nations, such as Indonesia, which tend to have densely populated urban areas where any infrastructural failure could be devastating to the safety of the people, as well as to the society and economy. Early Damage detection has paramount importance here to allow the repair of the structures so that they can continue to be used safely. Early damage detection has also been known to improve operational planning and reduce maintenance cost of the structure significantly**(Annamdas et al., 2017; Ganguli, 2010)**

The critical role of SHM to prevent structural failures has been evident through the case of KutaiKartanegara bridge. The structure of the bridge collapsed on November,26,2011**(Fergyanto Efendy Gunawan, 2018)**, due to a combination of overloaded use and undetected materials degradation of the important structural parts of the bridge, such as corrosion, and fatigue (which is time-dependent fracture failure), with many casualties. Moreover, SHM has been recognized to be effective method for rationalization of risk and asset management **(Fujino et al., 2019; Klerk et al., 2019; Law et al., 2014)**.However the full implementation of SHM into important engineering structures, such as bridges and aircrafts requires interdisciplinary approaches that integrate research activities focused on sensors, actuators, signal processing and interpretation, physics-based modelling, system integration, electronics, and computational techniques. Despite recent advances, there are still many challenges to overcome before SHM can be widely employed especially in important engineering applications that involve safety of people, such as in aerospace industries(**Inaudi, 2009; Ou & Li, 2009**).

Fiber-reinforced (carbon or glass) composite materials have increasingly been used especially in the aerospace industry – as lightweight but strong and tough materials are needed there – as well as in many other engineering fields such as automotive and energy industries. Composite materials have superior specific mechanical/structural characteristics (including fracture toughness and fatigue properties) compared to metals. However, they are known to be highly susceptible to damage caused by low or high-velocity impact loading, which is likely to occur especially in the case of aircrafts during their operations **(Ishikawa et al., 2018; Paixão et al., 2020; Yeager et al., 2017)**

SHM used to detect early damage in the composite materials in such complex structures such as in aircrafts led to the development of a vast range of techniques **(Giurgiutiu, 2019)**. Many ofthem used natural frequency while damage detection is global but less sensitive **(Fergyanto E. Gunawan et al., 2021; Fergyanto Efendy Gunawan, 2019)**. Various other methods for SHM on composite materials have been applied depending on the complexity of the damages and the structures. Euler-Bernoulli equation has been used to develop damage conditions and the integrity of material structures **(Fergyanto E. Gunawan & Sekishita, 2019; Fergyanto Efendy Gunawan, 2020)**and has been widely accepted that it offers high sensitivity for early damage detection.. Machine learning has also been widely used recently to predict various damages in structures. More Training and testing data are required to establish damage severity, damage index, and healthy condition **(Bao et al., 2020; Bao & Li, 2021)**.

Although, many SHM studies have been performed in structures made of fiber-reinforced composites, the response of structures especially with respect to low impact loading mode may be different as compared to metals **(Heimbs et al., 2010; Yang et al., 2016)**. Delamination (between layers or within each layer) is one example of such unique damage mechanism in composites **(Dogan et al., 2012; Hallett & Harper, 2015)**. Therefore, we propose here a new damage indicator which is based on the theory of strength of materials applied to plate geometry. A new damage index can be calculated by comparing the predicted deformation at a specified location with respect to impact loading and the actual measured deformation (through strain gage measurement, for instance). We predict the deformation using combination of plate theory and finite element modelling (FEM). We compare the results of our methodology with similar data obtained by other methodology as reported in the literature.

2.Methodology

2.1 Simulation Modelling

In this study, literature studies from related research journals were conducted. Literature study as input in conducting simulations on materials in terms of material selection, orientation angle, impact speed. The next stage is writing a proposal with a writing structure consisting of an Introduction (Background, Problem Formulation, Objectives, and Benefits), Theoretical Basis, Research Methods, Analysis Results, and Conclusions. Furthermore, a simulation model was made using the LS-DYNA (R) 4.6.19 software, the model that had been made was validated to ensure that the loading model on the composite plate was not damaged.

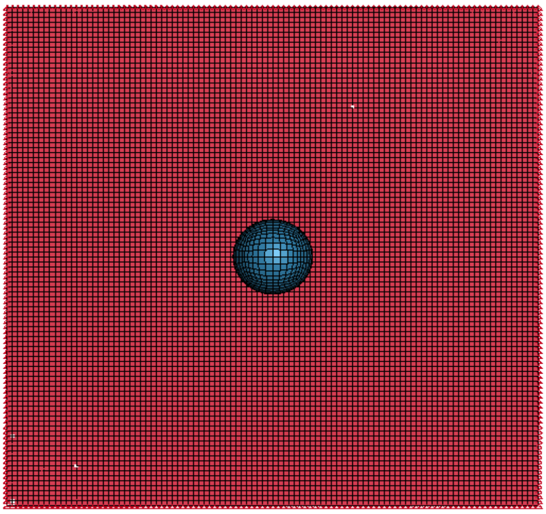


Figure 1. The simulation modelling of composite material under low impact loading

On figure 1 Composite plate in ls-Dyna was designed using 4N plat on shape meshes. The size of mesh respectively 2 mm. All the edges of plates are supported by simply supporting. The plates are subjected to low impact loading on the middle of a surface. The impact loading was restricted to the z-direction. Data of displacement of the z-direction is carried out on each node element that is in the middle layer of the surface of the composite plate.

2.2 Material

The material used in making the composite plate is carbon fiber (CF) which consists of combinations layer [0,90,90,0], thenanothercombination on the layer orientationssuch as [0,15,30,45,60,75,90,105,120,0] and [0,45,90,135,180,225,270,315,360,0]were used to ensure the validated modelling. The dimensions of the composite plate used are Length: 100 mm, width: 100 mm, and thickness: 0.4 mm. Impact loading using a steel ball with a radius of 30 mm. the loading does not cause failure on the plate surface. The mass of the ball is 0.1 kg with an impact velocity of 1 mm/ms. Mechanical properties of carbon fiber were seen in table 1(***Mechanical Properties of Carbon Fibre Composite Materials*, 2016).**

Table 1. Mechanical properties of Carbon Fiber Composite Material used in simulation modelling

Properties	Simbol	Unit	Std CF
Young Modulus 0° Young Modulus 90°	E1 E2	Gpa	70 70
Poisson ratio	V12		0.1
Ultimate Tensile strength 0° Ultimate compression strength 0°	Xt Xc	Mpa	600 570
Ultimate Tensile strength 90° Ultimate compression strength 90°	Yt Yc	Mpa	600 570
Ultimate Tensile strain 0° Ultimate compression strain 0°	ext exc	%	0.85 0.80
Ultimate Tensile strain 90° Ultimate compression strain 90°	eyt eyc	%	0.85 0.80
density	ρ	g/cm3	1.6

2.3 Structural Health Monitoring

Structural health monitoring using strain gauge as a sensor on the surface of the plate. The sensor is used to obtain the necessary data of deformation. This research takes the sensor on the node. The node was chosen at the around of impact area on the surface. Displacement to the z-direction could be taken from the respective nodes. Displacement to the z-direction at the node was used to determine damage index in the composite plate. The Kirchhoff-love dynamic equation which used to calculate damage index. The equation on an isotropic plate is proposed as follows

$$D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 \partial y^2}+\frac{\partial^4 w}{\partial y^2}\right)+q\,(x,y,t)+2\rho h\,\frac{\partial^2 w}{\partial t^2}=0 \tag{1}$$

Where,w:Plate Deformation (mm), q: Impact Load (kg), Density of material (kg/mm3), d: Damage index. displacement to the z-direction (w) is a function of time (t) which is derived respectively from the X and Y axes. The dynamic equilibrium equation is applicable for any point at the beam at any time. We hypothesize that a deviation from the condition may signify a change in either the material properties or the plat geometry or both.

In this work, we use the Kirchhoff-love plat theory not to predict a plat deformation, nor to predict theexerted force, but to estimate the plat integrity. For the purpose, we propose:

$$d(x,y,t)= D\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial^4 w}{\partial x^2 \partial y^2}+\frac{\partial^4 w}{\partial y^2}+q\,(x,y,t)+2\rho h\,\frac{\partial^2 w}{\partial t^2}\right. \tag{2}$$

we hypothesize when the plat in intact, and D, ρ, are assigned with values in the intact condition, the damage indicator (d) should be zero or very small. The indicator may shift from zero when the plat contains damage. We assume that damages alter plat deformation w(t,x,y). we compute the term $\partial^4 w/\partial x^4$, $\partial^4 w/\partial y^4$ and $\partial^4 w/\partial x^2 \partial y^2$ respectively by the finite element approximation of:

$$\frac{\partial^4 w}{\partial x^4}=\frac{\partial^2}{x^2}\frac{\partial^2 w}{\partial x^2}=\frac{w(i+2,j,t)-4w(i+1,j,t)+6w(i,j,t)-4w(i-1,j,t)+w(i-2,j,t)}{\Delta x^4} \tag{3}$$

$$\frac{\partial^4 w}{\partial y^4}=\frac{\partial^2}{y^2}\frac{d\partial^2 w}{dy^2}=\frac{w(i,j+2,t)-4w(i,j+1,t)+6w(i,j,t)-4w(i,j-1,t)+w(i,j-2,t)}{\Delta y^4} \tag{4}$$

$$\frac{\partial^4 w}{\partial x^2 \partial y^2}=2\frac{\partial^2}{\partial y^2}\frac{\partial^2 w}{\partial x^2}=2\frac{\partial^2}{\partial y^2}\left[\frac{w(i+1,j,t)-2w(i,j,t)+w(i-1,j,t)}{(\Delta x)^2}\right] \tag{5}$$

$$\frac{2w(i+1,j+1,t)-4w(i+1,j,t)+2w(i+1,j-1,t)-4w(i,j+1,t)}{(\Delta y)^2(\Delta x)^2}+\frac{+8w(i,j,t)-4w(i,j-1,t)+2w(i-1,j+1,t)-4w(i-1,j,t)}{(\Delta y)^2(\Delta x)^2}+\frac{+2w(i-1,j-1,t)}{\Delta y^2(\Delta x)^2} \tag{6}$$

As for the term ∂2w/∂t2, we firstly fit the displacement time-history data with a cubic spline function and then take the first and the second derivatives of the function to provide the acceleration. The derivation of the cubic spline function is as the following

$$\frac{\partial^2 w}{\partial t} = \frac{w(t+1)-2w(t)+w(t-1)}{t^2} \tag{7}$$

3. Results and Discussion

3.1 Results of the Finite Element Simulation: Impact between the Sphere and the Plate

Figure 3.1 shows the position of the sphere and the composite plate for various time instances during the impact from the side of the model. Initially, the gap between the sphere and the plate is xxx mm. The sphere impinges the plate at the initial velocity of 1 mm/ms. As shown in the figure, the sphere has contacted the plate surface at the time of t=1.49 ms. The sphere exerted sufficient force to deform the plate laterally. As a result, at the time t=5.5 ms, the plate has reached its maximum deformation. Finally, at the time instant of t=5.6 ms. The sphere has bounced back and completely lost contact with the plate.

t=0.38876 ms

t=1.4399 ms

t=1.49 ms

t=5.5 ms

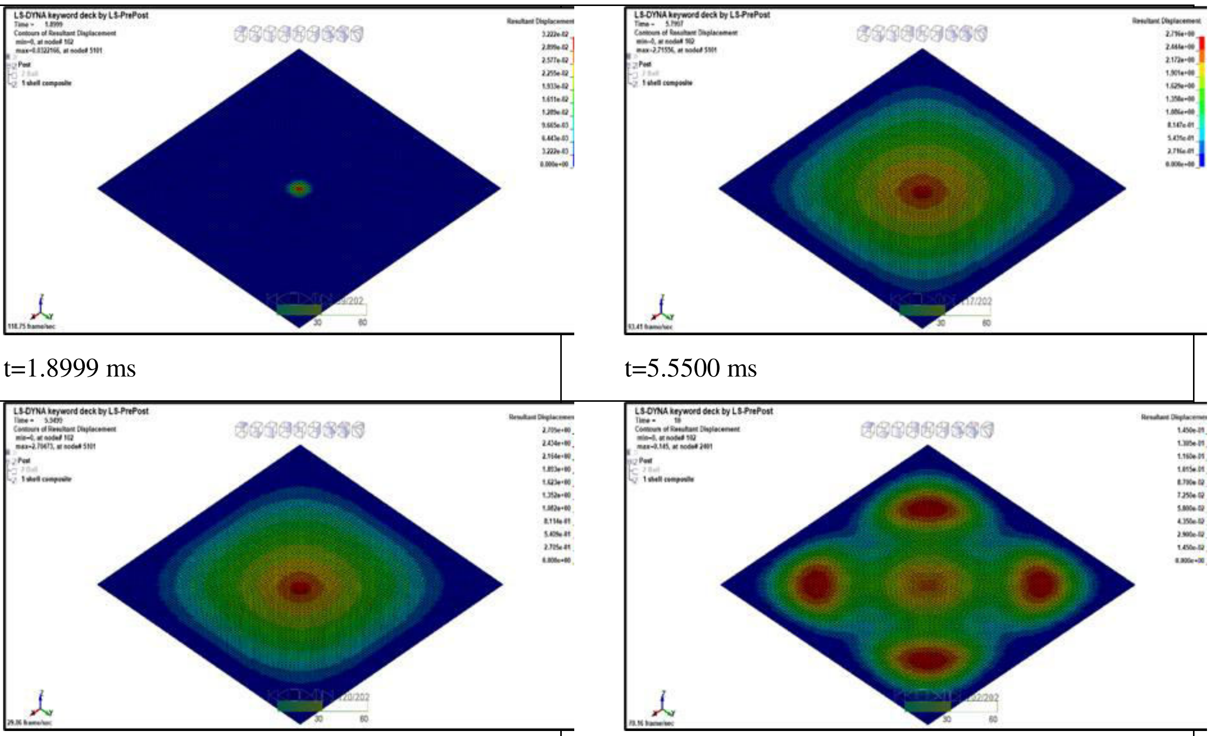
t=5.6 ms

t=10 ms

Figure 3.1: Impact between the sphere and the composite plate

3.2 Results of the Finite Element Simulation: Deformation of the Composite Plate

Figure 3.1 shows the lateral plate deformation for the four-time instances across the plate geometry. We note that the contact duration is extremely short, shorter than 8 ms. Initially, the plate deforms significantly at the plate center. The stress that is initiated at the plate center spreads out quickly to the whole plate. Similarly, the deformation field is mainly concentrated around the plate center. However, at the time instance of 10 ms, the deformations near the four corner points have become larger than the deformation at the center.



t=1.8999 ms

t=5.5500 ms

t=6.2499 ms

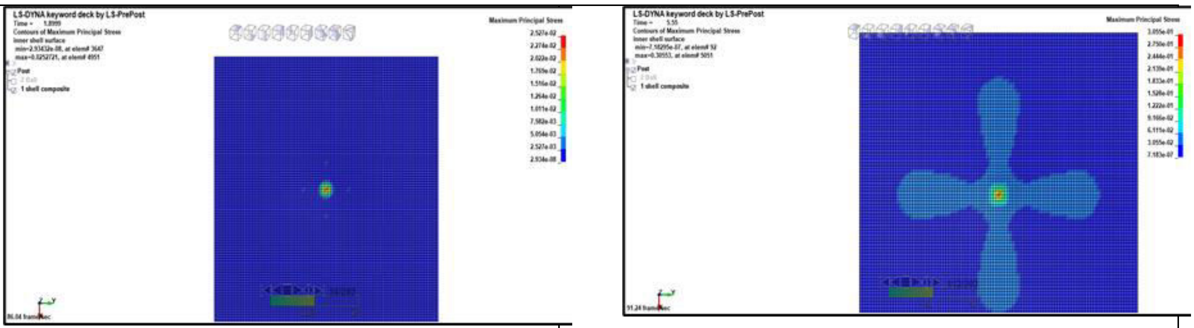
t=10.000 ms

Figure 3.2: The distribution of the plate displacement during impact.

3.3 Results of the Finite Element Simulation: First PrincipleStress on the Laminate

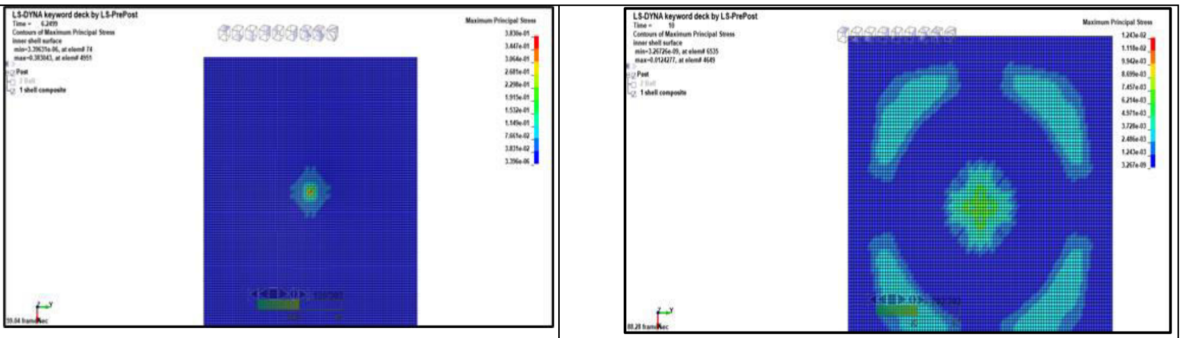
The distributions of the first principal stress (s1) for some time instances are depicted in Fig.3.3. Initially, when the sphere firstly impinged the plate, the stress is concentrated at the plate center where the impact occurred. As can be seen in the figure, at the time t = 1.89 ms, the first principal stress has reached the value of 0.025 Gpa. As the time progressive, the stress increases for a maximum value of 0.380 Gpa at the time of 6.24 ms. Over time, the stress reduces and reaches the value of 0.012 at the time of 10 ms.

The figure also shows that the stress mainly concentrates on the center of the plate. In addition, due to the complex stress reflection, the stress is also concentrated on the regions around the symmetric lines



t=1.8999 ms

t=5.5500 ms



t=6.2499 ms

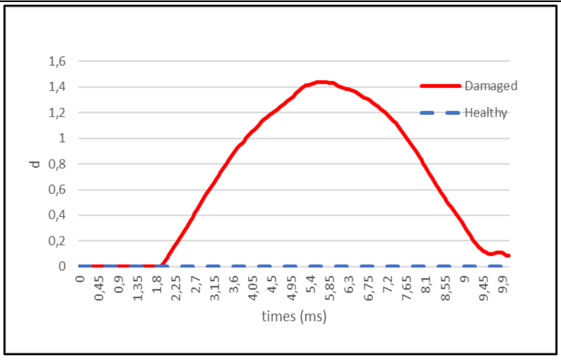
t=10.000 ms

Figure 3.3: The distribution of the first principal stress at some time instances.

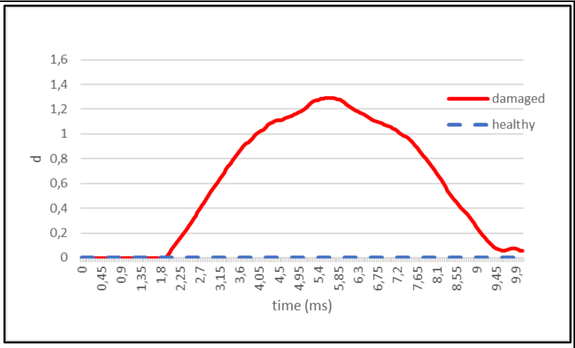
3.4 Results of the Structural Health Monitoring (SHM) on the laminate

Figure 3.4 show that at node 4593 which is at a position x = 10 mm and y = 6 mm from the center of the impact load, after monitoring the condition of the integrity of the plat surface, it is indicated that damage has occurred, with an index value of 1.44. At t = 0 ms to t = 2 ms, it looks like there has been no sign of change, the largest index when the ball has an impact on the plat is at t = 5.5 ms.At node 4492, which is at a distance of x = 12 mm and y = 6 mm from the impact load, after monitoring the condition of the plat surface at these nodes, it is indicated that damage has occurred with an index value of 1.29. the damage index at node 4593 which is close to impact load is greater than node 4492 **(Fergyanto E. Gunawan et al., 2021).**

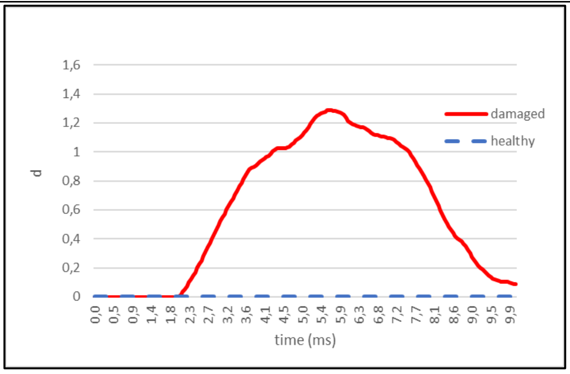
Similarly, the damage index at node 4391 has a position of x = 14 mm and y = 6 mm. The index value that occurs is 1.28, which is smaller than at node 4492.At node 4290 with a distance of x = 16 mm and y = 6 mm there is a smaller damage index compared to node 4391, the magnitude of the damage index is 1.23. And at the farthest node, 3675, it has the lowest index of 1.1.



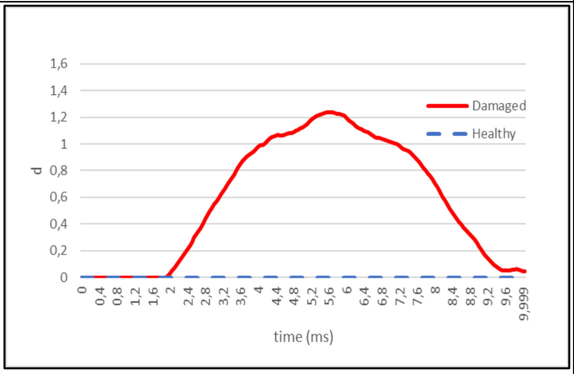
Node 1 =4593



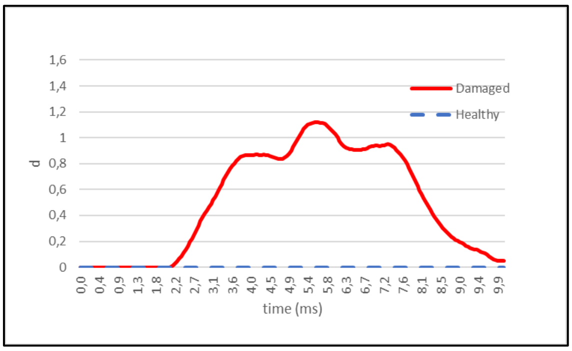
Node 2 = 4492



Node 3 = 4391



Node 4 = 4290



Node 5= 3675

Figure 3.4: The indicator d computed at the observation nodes located at 4593, 4492,4391,4290, and 3675 for the healthy and damaged condition.

4.Conclusion

The modelling of the composite plat on low impact loading is carried out using the finite element method. Monitoring the condition of the composite structure with the development of methods based on the strength of the material that has been carried out in this study shows indications of damage to the composite plat in areas affected by low impact. The modelling of the composite plat on low impact loading is carried out using the finite element method. The indication of damage is measured through the extraction of z displacement data on the element nodes. Based on the strength of the material, it provides local and global damage information, easy data collection and measurement.An experimental approach on a composite plat is needed to build a valid model based on the simulation. And further research can be carried out on solid composite elements so that the use of composite materials and their compositions can be applied.

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