Simulation of Impact Damage in a Composite Plate and its Detection

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Abstract: A problem of damage prediction in aircraft structure and its non-destructive evaluation is very important for aircraft structural health assessment.
The low-velocity impact was simulated. For laminate usually it associated with delamination which effect to compressive strength of long fiber composite is very significant. This damage is internal and its non-destructive detection is important for system of aircraft structural health monitoring (SHM). The analysis of the features of direct impact of thin-walled laminate component of aircraft was performed by COMSOL Multiphysics software. Some regularities of ultrasonic guided wave propagation in composite sheet with different kinds of damage were investigated by the simulation and compared with the special test. New approach for detection of delamination in composite plate is developed.

Keywords: impact, composite, delamination, ultrasonic detection

1. Introduction

COMSOL Multiphysics software was using for modeling of processes connected with the strength of the thin-walled long fiber reinforced composite structure: low-velosity and middle-velosity impact, the typical kinds of damage, estimation of remaining strength and lifetime of damaged structural element, selection of effective solutions of damage detection and structural health assessment.

Laminated composite materials use extensively in number applications especially in aerospace structures mainly due to their high specific stiffness and strength. However, their behavior under impact loading that is typical at manufacture, operation, and maintenance. Impact is especially critical, if it induces significant internal damage, undetectable by visual inspection. Impact dynamics, including the motion of both the impactor and the target and the force developed at the interface, can be predicted accurately using a number of models.

2. Low-velocity impact of laminated composite

The special simulation was done for definition of valid limits of model at investigation of low-velocity impact of the laminate composite plate. For comparison the result of impact test of 2 mm thick GFRP round plate (76.2mm diameter) described in [3] was used. The tests were performed using a free-fall drop dart machine: the maximum impact energy is limited by the fixed mass 20 kg, of the impactor and the falling height. As a results, the impact energy was varied in range from 20 to 54J. Three cases were realized:

- Free fall, stop, rebound of impactor;
- Free fall and impactor stop;
- Free fall and perforation.

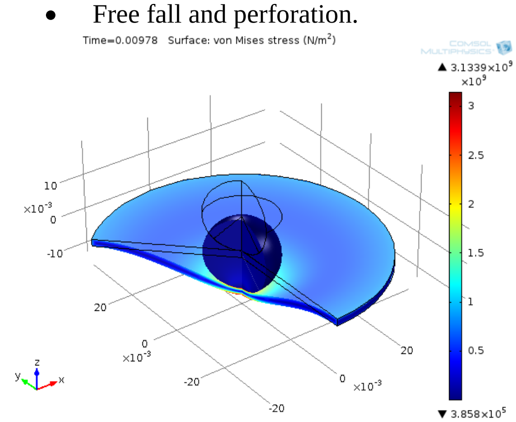

Figure 1. Dynamic contact interaction of steel ball with diameter 8 mm with 76.2 diameter plate

COMSOL model of this test is presented in Figure 1. The round plate fixed on external boundary was subjected to impactor with spherical surface. It is dynamic contact problem [4] that in linear case can be simulated by COMSOL Solid Mechanics tools.

In first case of impact the results of modeling practically coincide with test. But if energy of impact is equal or more than so called saturation energy that shows level of material resistance to penetration of impactor, then the results of simulation only partly correspond to test.

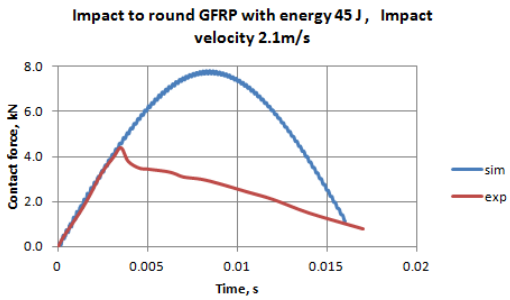

Figure 2. Comparison contact force simulation with test

Figure 2 shows that in second case of impact (free fall and impactor stop) the simulated contact force at load increasing practically coincides with test result. Similar conclusion is for displacement prediction (Figure 3). However, at second stage of impact difference between test and simulation is very significant. Fortunately partial damages of composite (matrix cracking, delamination) develop mainly at first stage. So additional data processing with special Matlab code allows predicting of these defects of structure.

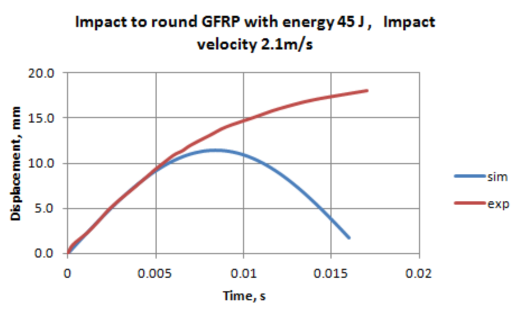

Figure 3. Comparison of impactor displacement simulation with test

3. Simulation of Guided Wave Application for Delamination Detection in Layered Composite

3.1. 3D simulation

A problem of damage prediction in aircraft structure and its non-destructive evaluation is very important for aircraft structural health assessment.

The analysis of the features of direct impact of thin-walled laminate component of aircraft was performed by COMSOL Multiphysics software. The effect of materials of contact pair, geometrical form of projectile, its mass and initial velocity as well as also structure of the thin-walled composite plate, material performance, boundary conditions and others parameter was investigated. Mainly the GFRC and CFRC laminates were selected in form either thin separate plate or sandwich structure.

For laminate usually it associated with delamination which effect to compressive strength of long fiber composite is very significant. This damage is internal and its non-destructive detection is important for system of aircraft structural health monitoring (SHM).

There are large number of publications dedicated to problem of laminated composite delamination and the methods of its prediction [5-9]. The experimental technique and technology also is one of the most actual problems.

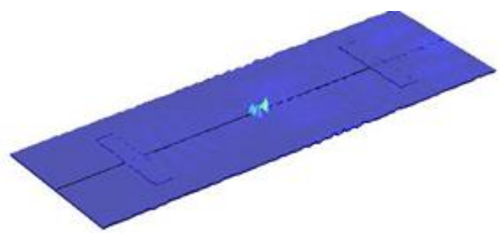

Figure 4. Simulation C-scan of a composite plate by ultrasonic method

The simulation of A-scan and C-scan (Figure 4) procedures using ultrasound Lamb wave technology was performed. The GFRP plate 1x80x240mm instrumented by two piezoceramics transducers was modeled by COMSOL software. In center of a plate the 10x10 mm delamination was modeled. The signal generated by one transducer (actuator) was received by opposite one (sensor). It is the model of A-scan that extensively uses the aircraft SHM system. Simulation result shows that as the transmitted as reflected signals practically do not have any changes in comparison with non-damaged plate.

If the C-scan is modeled (Figure 4), then the transverse displacement up delamination is very

well detected. The cause of this difference is investigated and presented below.
Some others regularities of ultrasonic guided wave propagation in composite sheet with different kinds of damage were investigated by the simulation and compared with the special test

3.2. 2D modeling of guided wave propagation in the laminated composite

The essential properties of classical Lamb wave propagation in composite layer and its interaction with delamination were investigated by computational simulation (2D problem). The sheet of composite material of t =1 mm thickness and L =1000 mm length was simulated by dynamic finite element method (Figure 5). The Academic Research COMSOL Multiphysics software was used for simulation of guided wave propagation and its interaction with damage. The effective elastic properties of CFRP with 55% fraction of the carbon fiber were introduced by orthotropic material. The planes of symmetry of elasticity are coincident with planes of symmetry of a sample. Delamination of composite was modeled by a narrow split with 0.1 mm width and length d =1-15 mm.
At FEA the mesh of FE has a local refining. As a result the average size of FE in a box around a split was smaller than width of a slit.

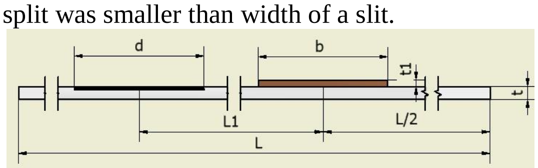

Figure 5. The scheme of a sheet of composite material with parameters: $\boldsymbol{t}$ =1 mm, $\boldsymbol{L}$ =1000 mm, $\boldsymbol{t}$ =1 mm, $\boldsymbol{L1}$ =250 mm.

Of course this model of delamination is not completely correct because avoids contact interaction of split sides, but the effect of actual delamination to elastic wave and finally to signal of a sensor should be similar.
Upper surface of this virtual sample was equipped by the $t1 \times b =$ 0,5x10 mm piezoelectric transducer in center of sample. It was used for simulation of a pulse of elastic wave.

The wave was generated by the burst of sine function modulated by the error function.

$$E(t) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{t-t_0}{\sigma}\right)^2} sin\omega t, \qquad (1)$$

where $\omega = 2\pi f$, f is basic frequency of excitation, $t_0 = 3\sigma$, $\sigma = \frac{\pi n}{3f}$, and n is number of sine waves in the burst.
The basic frequency of excitation was equal 250 kHz. The phase velocities of S_0 and A_0 modes of Lamb wave propagation are equal to 5310 and 1820 m/s respectively .
The some results of simulation of wave propagation and its interaction with delamination are presented below.
The displacements of surface of a sample for initial generation and after the S_0 mode reflection is presented in Figure 6 for undamaged state of a sheet.

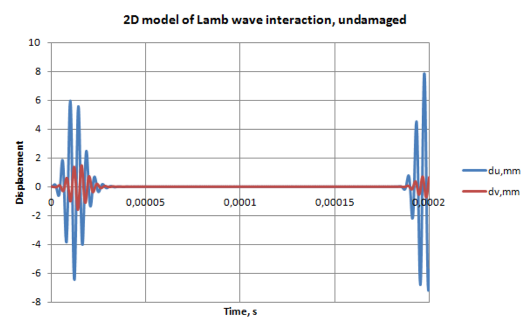

Figure 6. The displacements of surface of a sample for initial generation and after the S_0 mode reflection for undamaged state of a sheet

All time of direct and opposite this mode of wave propagation is equal about 1.85e-4 s. The same plot for a sheet with 5 mm delamination is shown in Figure 7.

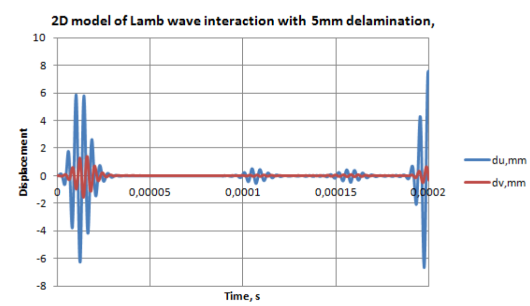

Figure 7. The displacements of surface of a sample with 5 mm delamination

It can see the two weak signals were received by sensor before occurrence of the S0 mode reflected signal. It is reaction to delamination in composite.
First of them is the result of the S_0 mode interaction with delamination, but second is also the S0 mode as a conversion of A_0 mode to symmetrical one. Of course these signals could be used for health monitoring of structure, but the probability of detection is low. At the same time the reflected signal of A_0 mode is much more (Figure 8). But the used transducer is not tuned to receiving of A_0 mode.

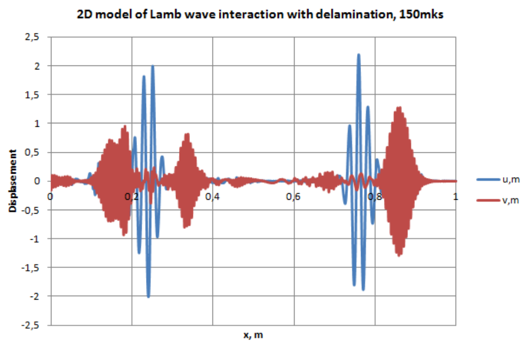

Figure 8. At the left-hand side the reflected A_0 mode is shown (compare with the right-hand side)

The corresponding additional transducer or its specific form should be used for effective health monitoring of composite with delamination. Possible shape of combined transducer that is tuned to receiving of the S_0 mode as well as A_0 mode is presented in Figure 9. The height of vertical part of transducer is calculated by follow formula:

$$h_1 = \frac{L_1}{2} = \frac{c_2}{2f} \ , \qquad (2)$$

where c_2 is velocity of A_0 mode propagation.
Figure 10 shows the effect of application of such combined transducer. It can see that reflected the A_0 mode of a wave from delamination is very significant and well detectable. In the Figure 10 the displacements those define received signals are: du defines the S_0 mode of reflected signal (blue line), dv defines the A_0 mode of signal that reflected from damage (red line), and $dv0$ defines the A_0 mode of a wave at initial shape of transducer (yellow line) without vertical part.
Additionally the 3D simulation of delamination was done for a plate of the same composite material with 10x10 mm delamination. There was shown that the C-scan is the most effective approach of delamination detecting.

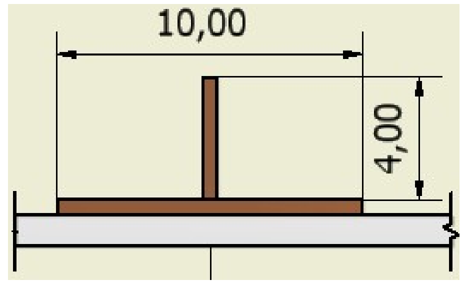

Figure 9. The modified transducer

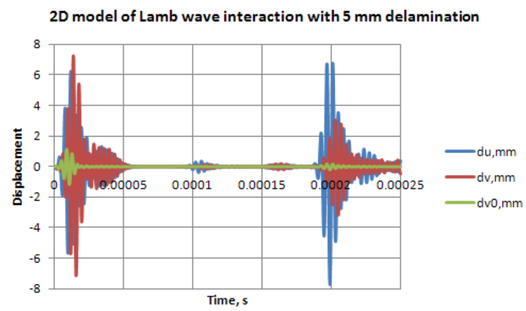

Figure 10. The effect of application of such combined transducer

7. Conclusions

The COMSOL Multiphysics is good tool for simulation and analysis of dynamic problems at the creation and optimizing of system of aircraft structural health monitoring.
The composite structure response to low-velocity impact of composite structural element can be well predicted at first stage of impact using the approach developed and described above. It allows to predict principal results of impact and damages of structure. There is needed further improvement of this technique for full description and simulation of impact phenomena.
The S_0 mode interaction with delamination is relatively weak and insufficient for reliable evaluation of this kind of damage. The A_0 mode interaction with delamination induces conversed S_0 mode that also has small amplitude.
The reflected A_0 mode is significantly more than mentioned ones. But for its effective detection the separate transducer is needed.
Special combined transducer could be good solution for delamination detecting

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