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MECHANICAL Hysteresis AS AN NDE TOOL FOR EVALUATING COMPOSITE HONEYCOMB DAMAGE

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ABSTRACT. Honeycomb composites are finding ever increasing use on aircraft structures, making nondestructive detection of defects contained within honeycomb structures all the more important. This paper focuses on a new detection technique which makes use of the mechanical hysteresis seen as loops in the force-displacement curves. It was observed from load test data that internal damage in honeycomb sandwiches causes the average slope of the force-displacement curves to decrease and the area contained within the hysteresis loop to increase. To satisfy the inspection speed and one-sided access requirements of NDE techniques, a dynamic loading approach was pursued where an accelerometer was used to tap the surface of the test sample. Much of the research focused on the deduction of the force-displacement curves from an acceleration curve. This greatly increased the speed of the technique as well as reduced it to a one-sided test, where only access to the outer surface of the structure is needed.

Keywords: Nondestructive Evaluation, Mechanical Hysteresis, Tap Test, Honeycomb Composite Structures, Low Frequency NDT
PACS: 81.70.-g

INTRODUCTION

"Hysteresis is a property of systems (usually physical systems) that do not instantly follow the forces applied to them, but react slowly, or do not return completely to their original state: that is, systems whose states depend on their immediate history," as stated in Wikipedia[1]. The hysteresis phenomenon is found in several disciplines including electricity, magnetism, and mechanical systems. The hysteresis loop appears in the stress-strain curve of honeycomb composites where the stress is not only dependent upon the instantaneous value of strain but also the history of the loading phase. Each value of strain will correspond to two different values of stress, one being on the loading phase and the other on the unloading phase. This causes the loop effect, shown in Fig. 1, which is a strong indicator of hysteresis.

It was found in the course of study of honeycomb composite damage that the area enclosed by the hysteresis loop is correlated to the level of damage in honeycomb composite materials. The physical meaning of the area enclosed by the loop is absorbed energy. More specifically, it is the energy absorbed by the structure due to internal frictional forces. When a crack or buckle develops in a honeycomb core, the number of surfaces where frictional loss can occur increases. In the case of a crack in fiber reinforced composites, the level of frictional loss should increase dramatically due to fibers intertwining with each other when compressed and then having to untangle as the load is reduced and the structure returns to its original shape.
FIGURE 1. Typical stress-strain curve showing a hysteresis effect.

With regard to the inspection of honeycomb composite structures for detection of in-service damage, the tap test is predominantly the method of choice [2]. The test is simple, inexpensive, and relatively sensitive to damage, but suffers from an inability to differentiate the various types of damage, such as crushed or buckled cores, skin/core disbonds or inter-ply skin delaminations. In the airline maintenance community, knowledge of the type of damage present has an impact on repair operations, with crushed/buckled (but still bonded) cores treated as a cosmetic repair, whereas disbonds and delaminations require more extensive (and expensive) repairs. For these reasons, it was proposed to evaluate an extension of the tap test and gage the ability of a tap test deduced hysteresis measurement to differentiate damage types in honeycomb composites.

QUASI-STATIC LOADING

When generating a stress-strain curve, structures may be loaded in two manners. Quasi-static loading, being one method, allows the structure sufficient time to adjust to the load, providing the maximum amount of frictional loss to take place. However, these tests take much longer to perform and are unsuitable, from a time standpoint, when attempting to test the entire surface of a structure. The purpose for these static loading tests is to verify the theories, the correlation between loop area and damage, experimentally. Upon verification of these theories, the issue of slow loading times can be addressed and a dynamic loading setup can be investigated. A sample commercial grade structure from Scale Composites was obtained for experimentation. Varying degrees of damage were induced on the structure via drop weight impacts, with each impact region identified on the surface of the structure by number. The level of damage, i.e., the amount of potential energy in the impact, was calculated for each impact. The energy calculated was later used for comparison between flaws. Using a manual loading setup, hysteresis loops were generated while loading the Scaled Composites sample. Figures 2 and 3 represent positive correlation between loop area and impact energy. The stiffness of the impacted regions also seems to correlate well with impact energy, i.e., the greater the impact energy, the lower the stiffness after the impact.

DYNAMIC LOADING

The method of dynamic loading can also be used to generate a stress-strain curve. Dynamic loading allows the structure little time to relax and relieve the stress compared to static loading. Loading curves are generated quickly, having total loading times of the order of one millisecond. Although, because dynamic loading allows little relaxation time,
FIGURE 2. Hysteresis loops produced from the Scaled Composites test structure when statically loaded using the manual loading setup.

FIGURE 3. Absorbed energy curve on Scaled Composites panel using INSTRON machine.

the issue of whether the stress-strain curve shows a hysteresis effect becomes a concern. Initial quasi-static load testing showed that loading rate strongly affected the size of the hysteresis loop. Figure 4 displays the results of additional test performed which varied the load step size during quasi-static loading, where step size variation is directly proportional to loading rate. If the curve in Fig. 4 is interpolated to infinity, representing increasingly higher loading rates that approach the rates in a dynamic test, loop areas should approach a constant value.

Figure 5 graphically shows the difference in loop area of quasi-static and dynamic tests shown in Fig. 4. Each graph shows two hysteresis loops generated over the same position on the sample, one using static loading (solid black) and the other dynamic loading (dashed grey). The dynamic tests were produced by tapping the surface with an accelerometer with a hemispherical tip attached, as described in [3,4]. Note, first, that the slopes (the upper portion of the loop, from initial load to peak) of the two loops are quite similar. Note also that the shapes of the loops are also quite similar, and the peak loads for dynamic tests are lower, which was found consistently throughout the tests. The reasons for evaluating dynamic tests are two-fold: a dynamic test is faster, and dynamic tests can be conducted with access to only one side of the honeycomb panel.

For hysteresis measurements, load is relatively simple to measure with one sided access; however, displacement proved to be a great challenge and the majority of the research performed was devoted to this topic. The method considered makes use of an accelerometer similar to that of the CATT systems tap test. When tapped on the surface of
the structure, the accelerometer measures acceleration as a function of time. Theoretically, this curve could be integrated twice to produce a displacement curve (details of this are discussed later in this paper). The load (i.e., force) is obtained using the instantaneous values of acceleration based on $F(t) = mA(t)$, where $m$ is the known mass of the accelerometer. The method requires only one-sided access and provides a very quick process of obtaining a load-displacement curve. This method has the potential for being a viable technique of obtaining a hysteresis loop by simply tapping the surface of the structure.

**TAP TEST ACCELERATION CURVES**

The typical signal output of an accelerometer from a tap is usually a bell-shaped curve. As the tapper mass compresses the structure, the instantaneous acceleration increases to a maximum which corresponds to the point of maximum deflection of the surface. As the structure begins to return to its original shape, the accelerometer begins moving in the opposite direction, decreasing in acceleration from the initial maximum to near zero where the accelerometer is no longer in contact with the surface. A slight asymmetry with respect to time is often observed in the signal output of the accelerometer. This asymmetry is usually small and the signal output can be modeled approximately as the half cycle of a sine wave. A flaw in the composite affects the signal output of the accelerometer. The acceleration curve produced over a flawed region commonly has a lower peak acceleration and longer probe-to-surface contact duration relative to a non-damaged region. The curve appears to be compressed vertically and stretched horizontally. The peak acceleration depends strongly on the force used in the tapping, but the contact duration is largely independent of the tapping force [3]. With a method or mechanism to apply constant tap force, either of these two parameters could be used to differentiate a
damaged region from an undamaged region. With hand taps, contact duration, \( \tau \), has proved to be a more stable and easily measured parameter.

When a manual tap test is used for dynamic hysteresis measurements, the operator must impact the structure by hand using the tapper to strike the surface of the structure. Clearly, impact force cannot be considered a constant, so comparisons of hysteresis loop areas would be problematic. Figure 6 demonstrates the result of normalizing the peak acceleration of each tap test, where testing showed that normalization does not affect the shape of the acceleration curves. Two curves (right) were obtained over the same point but with different tap forces, then normalized and plotted (left), where the two curves lay directly on top of each other.

**DEDUCTION OF A FORCE-DISPLACEMENT CURVE FROM TAP TEST ACCELERATION DATA**

Acceleration can be integrated to provide velocity, which in turn, can be integrated to provide displacement. The constants of integration, for example, initial velocity and displacement, \( V_0 \) and \( D_0 \), must be known to solve for correct values of displacement and velocity. The results obtained from integrating acceleration are shown in Eqs. 1-3, where \( V_0 \) and \( D_0 \) are the constants of integration.

\[
F(t) = ma(t) \quad (1)
\]

\[
V(t) = \int A dt = At + V_0 \quad (2)
\]

\[
D(t) = \int V dt = \int (At + V_0) dt = At^2 + V_0t + D_0 \quad (3)
\]

Before the constants of integration are solved, the area integral must first be addressed. The data received by an oscilloscope from the accelerometer is discrete, and so a discrete integration technique can be used to integrate these curves. A positive acceleration will be defined as being normal to sample surface and opposite in direction of initial velocity (into the part), with zero displacement defined as the undisturbed structure surface and displacement into the part positive. This leaves only the initial velocity, \( V_0 \), to be solved, for which one boundary condition is needed. There are three different methods for which the initial velocity can be determined. The first method used is shown in Eq. 4, where the inflection point of the velocity curve (peak of acceleration) is set to zero.

![Figure 6](image-url)

**FIGURE 6.** Result of normalizing acceleration data to uniform peak values, with data before normalization, left, and normalized, right.

\[
A(t) = \max \text{ at } t = t_1 \quad (4)
\]

\[
V(t_1) = 0
\]
The selection of the inflection point can be difficult due to noise; therefore, a new method was derived which makes use of the second zero crossing of the displacement curve. The boundary conditions are shown in Eq. 5.

\[ A(t) = 0 \text{ at } t = t_2, \text{ where } t_2 \neq 0 \]

\[ D(t_2) = 0 \]

(5)

However, this method began to fail, producing unrealistic results where the hysteresis loops inverted, indicating an increase in total energy. An unusual phenomenon was observed where the displacement curve dipped slightly below the x-axis before returning to the baseline. Eq. 5 was modified slightly to accommodate for this dip below the baseline. This method is an iterative method which forces the displacement curve to return to the baseline. This condition comes from the assumption that the sample is able to fully return to its original state after it has been impacted. Eq. 5 makes use of the point where the acceleration curve first crosses the baseline. Eq. 6 makes use of the minimum point on the acceleration curve. Curves generated using Eq. 6 did not produce unrealistic hysteresis loops; hence, this boundary condition was used for the remainder of our experiments.

\[ A(t) = \min \text{ at } t = t_3, \text{ where } t_3 \neq 0 \]

\[ D(t_3) = 0 \]

(6)

To test the hysteresis loops being produce, a stiffness correlation was used. Stiffness was calculated from the force-displacement curve by calculating the slope to each individual point on the curve, and subsequently, taking the average of all the slopes to give an average slope for the entire curve. This value was then plotted against stiffness deduced from instrumented tap test, as shown in Fig. 7. The results displayed are quite good, with a slope close to unity. Of particular interest is the tight grouping of the data, with little spread. Given the amount of data collected, this is a good indication of the validity of the acceleration integration method and its corresponding force-displacement curve.

**BELL TEST PANELS**

Bell Helicopter provided honeycomb test panels, both of which have Nomex honeycomb cores and fiberglass/epoxy face sheets. The panel A was damaged with a 1.5 inch diameter steel ball dropped from various heights. The method for calculating damage was very similar to that used with the Scaled Composites panel; however, the rebound height was taken into account as a means of producing more accurate damage data. Panel C already contained embedded flaws when the panel was received.

Throughout the course of studies performed on these structures, an additional parameter was considered as a possible damage indicator. This parameter was the change in velocity of the accelerometer through the duration of the tap, more specifically it is the difference between the initial velocity and the final velocity of the accelerometer. This measurement is not sensitive to initial velocity because it measures the relative change in velocity from the point of impact, shown diagramatically in Fig. 8. Even with an incorrect initial velocity selection, the relative change in velocity remains the same. Much of the uncertainty associated with the process of selecting initial velocity is eliminated with this method, making the process very favorable from a data processing standpoint. Due to the normalization process, damaged areas show a higher change in velocity, \( \Delta V \), than non-damaged regions. The two panels were tapped on a 1cm grid pattern over the surface of the
FIGURE 7. Correlation between the stiffness computed from \( \tau \) and the stiffness computed from the force-displacement curve. The data points were collected over a 17x25 grid (425 data points).

FIGURE 8. Diagrammatic example of Delta velocity measurement.

sample, where the entire acceleration waveform was captured for each point to allow for the calculation of enclosed area, change in velocity, and \( \tau \) for each point. Contour plots of enclosed area and \( \Delta V \), were generated for each panel using a contour plot of \( \tau \) for comparison to a proven method. Of the three methods on the Bell samples, the enclosed loop area plots demonstrated the best contrast between flaw and non-flaw regions in Panel A, a large cell honeycomb panel with a relatively thin skin. This sample showed significant variability in response from non-flaw areas in the \( \tau \) and \( \Delta V \) images. The thicker skinned Panel C, conversely, showed little variability in response from non-flaw areas, and showed greater contrast in the \( \Delta V \) and enclosed loop area images, respectively. The tap test typically has an upper limit of 9-10 plies for good sensitivity to defects, and may require less mass (accelerometer and tup) to decrease sensitivity to core size effects for honeycomb composites with thin face sheet skins. The results are shown in Fig. 9 and Fig. 10.

FUTURE WORK

The acceleration integration method displayed very promising initial results, yet there is much work required to be completed in the future. A more reliable form of initial velocity selection must be developed. Setting displacement equal to zero at the point in time where the acceleration curve reaches a minimum, Minimum Acceleration Method, proved to work very well for the Bell Helicopter panels, yet intuitively, this method is not the most logical. It is assumed the accelerometer would register zero acceleration as it leaves the surface of the panel, not a negative acceleration. In order to acquire a full comprehension of this, the original two methods for initial velocity calculation, Inflection Point Method and Zero Acceleration Method, should be studied further. A clearer understanding of the reason these methods do not work may shed some light upon either why the third method does work or provide a better method for initial velocity calculation.
The fact that the accelerometer may leave the surface before the panel has returned to its original shape was not addressed in this research. A study of the tapper motion, including very accurate measurements of the motion of the transducer as well as the panel surface, may also help develop a more effective initial velocity selection technique.

A fast, simple data acquisition method must also be developed. The current method for collecting the waveforms of the accelerometer made use of high speed digital storage oscilloscope. The process of collecting data over a 10 by 10 centimeter grid took up to an hour, which is clearly unacceptable when considering the inspection of a real part. For use in the field, a simple and portable device is needed where technicians can be easily trained. The methods described here are not ready for the hanger floor; however, they show promise and hold the possibility of becoming a useful tool for honeycomb composite damage detection and evaluation.

REFERENCES