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THICKNESS EFFECTS ON IMPACT RESPONSE OF COMPOSITE LAMINATES

Basavaraju B. Raju[1], Dahsin Liu[2], and Xinglai Dang[2]
[1] U.S. Army Tank-automotive Research, Development & Engineering Center (TARDEC)
Warren, MI 48397
[2]Department of Materials Science and Mechanics
Michigan State University
East Lansing, MI 48824

SUMMARY

In an effort to understand the impact response of composite laminates, various degrees of impact ranging from subperforation to perforation were introduced to glass/epoxy laminates through an instrumented drop-weight impactor. In addition, composite laminates of two thicknesses were examined for thickness effects. Experimental results showed that thickness plays a very important role in impact resposne. The impacted composite laminates were then subjected to compression after impact (CAI) tests for characterizations of residual mechanical properties. Experimental results showed that perforation was the most important damage stage in composite laminates subjected to impact loading since impact characteristics (peak force, contact duration, and absorbed energy) and mechanical properties degradation (residual compressive maximum force and residual compressive absorbed energy) of composite laminates became stable once perforation took place. Since the impact response of composite laminates is due to plate bending to some extent, bending analysis was used to explain the thickness effect.

INTRODUCTION

Small coupons are usually used in laboratories for material characterizations. Results from small coupon tests are then used for large structural designs. However, small coupons do not always behave the same way as the large structures made of identical material. The difference of behaviors due to size change is usually called size effects. Some investigations regarding the performance of composite materials and structures at different sizes have been reported [1-5]. It has been concluded that size effects should be carefully examined in material characterizations and structural designs.

Size effects include both in-plane dimensional effect and thickness effect. The former has gained more attention than the latter possibly due to the fact that most conventional composite structures are made of thin laminates in which the aspect ratio of laminate dimensions versus thickness are greater than 20. As technologies of composite manufacturing advance and applications of composites to non-aerospace industries are increasing, more and more thick-section composites are used in structural designs. For example, thick-section composites used for submarine hull and armored vehicle bodies have been proved to be feasible designs. Since thick-section composites behave differently from their thin-section counterparts, there have been some investigations on thick-section composites [6].

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The study of size effects on impact-loaded composite laminates were focused on scaling laws and parameters. Morton [7] scaled both composite laminates and impact loading and verified the feasibility of using analytical scaling laws for predicting undamaged behavior. He also found that smaller specimens were always stronger than larger ones. In an effort to understand the scaling laws governing impact-loaded composite laminates, Qian, Swanson, Nuismer, and Bucinell [8] also verified that analytical scaling laws could accurately describe the undamaged response to impact. In addition, they concluded that the damage resulting from impact involved many complicated factors and the delamination size was consistent with the size effect. Aiming at simplifying the design procedures for scaling impact-loaded composite laminates, Sankar [9] presented semi-empirical formulae for predicting impact characteristics such as peak force, contact duration, and peak strain on back surface. No response beyond initial damage was investigated in his study.

In an effort to understand the thickness effects on the response of composite laminates subjected to impact loading, a whole-range investigation ranging from elastic impact, subperforation impact, to perforation impact, was performed. In order to assess the degree of damage and to characterize the residual mechanical properties of impacted composite laminates, compression after impact (CAI) testes were also applied to damaged composite laminates.

EXPERIMENTAL METHODS

1. IMPACT TESTING

In this study, impact tests were performed on a DYNATUP GRC 8250 impact testing machine as shown in Fig. 1. The impactor consists of three components: a dropping crosshead, an impactor rod, and an impactor nose. The steel impactor rod has a diameter of 12.5 mm and is attached to the dropping crosshead. A force transducer having a force capacity of 22.24 kN was mounted at the tip of the impactor rod and encapsulated by a hemispherical nose. The total mass of the impactor was 11.9 kg. For an impact velocity up to 4 m/s, the impactor was released from a chosen height up to 0.8 m and dropped freely along the loading frame. However, for an impact velocity higher than 4 m/s and up to 8 m/s, the impactor was raised to the highest point, i.e. 0.8 m, and a pneumatic unit located at the top of loading frame was used to provide an additional force to increase the impact velocity.

Cross-ply laminates made of 3M glass/epoxy composite were investigated in this study. Two nominal thicknesses with averages of 2.24 mm and 6.69 mm were used for studying thickness effect. The former had a stacking sequence of $[0_2/90_2/0_2/\ldots]_{18}$ while the latter $[0_3/90_3/0_3/\ldots]_{51}$. These two types of stacking sequences could be viewed as thickness scaling of mixed mode since it combined a sublaminate mode which increased the laminar number from 9 to 17 and a layer-level mode which changed the layer thickness from 2-layer to 3-layer per each lamina. In this study, the 2.24 mm specimens were called *thin* laminates while the 6.69 mm specimens were considered *thick* laminates.

In impact tests, composite specimens with dimensions of 250 mm x 175 mm were placed between two steel plates. Each steel plate had a square opening of 125 mm x 125 mm in the center. In the impact tests, each set of specimen and steel holders was bolted at four corners to the specimen frame which was fixed to a concrete floor as shown in Fig. 1.

As the impactor dropped and approached a composite specimen, it triggered two time sensors right before impact took place. The initial impact velocity could be calculated from the time interval required for the trigger to travel between the two sensors and the distance between them. Once impact began, the contact forces at many consecutive instants were detected by the force transducer. The force history was recorded in a computer. The maximum contact force was termed *peak force* while the overall time duration of contact, *contact duration*. The corresponding velocity history of the impactor could then be calculated from integrating the force history (after being divided by the mass of impactor, i.e. 11.9 kg) and with the use of initial impact velocity. Similarly, the corresponding displacement history of the impactor could be calculated from integrating the velocity history.

Based on the force and displacement histories of the impactor, the energy history, which represented the history of energy transferred from the impactor to composite, could be calculated. In this study, the *absorbed energy* was termed as the amount of energy transferred from the impactor to composite at the end of an impact event while the *impact energy* was the kinetic energy of the impactor right before impact took place. The peak force, contact duration, and absorbed energy, along with the histories of force, displacement, and energy, were found to be the important characteristics of composite laminates subjected to impact loading.

2. COMPRESSION AFTER IMPACT (CAI) TESTING

Since perforation and delamination were the dominant damage modes in impacted composite laminates and they strongly affected the compression performance of composite laminates, compression after impact (CAI) was commonly used in characterizing the residual mechanical properties of impacted composite laminates, e.g. Ref. [12-14]. In this study, the NASA's compression after impact test [15] fixture shown in Fig. 2 was used for determining the residual compressive stiffness and residual compressive maximum force of impacted composite laminates. In addition, the residual compressive absorbed energy was also determined.

In performing CAI tests, impacted composite laminates were cut into 250 mm x 125 mm. The specimens were snug-fitted in the CAI fixture by knife edges along the two longitudinal sides as depicted in Fig. 2. The specimens were further clamped at the top and bottom ends. Gaps of about 10 mm were left between the clamping ends and the top and bottom ends of knife edges, allowing the specimens to shorten during compression tests. A crosshead speed of 3.81 mm/min was chosen in compression tests. The CAI tests worked well for most thick composite laminates except for a couple of cases in which local damage due to crushing of laminate at clamping ends (top or bottom) took place when the composite laminates had either very small or no impact-induced damage. In order to avoid the local crushing damage, especially for those with small or no impact damage, end tabs were bonded to composite specimens. For thin specimens, extra long end tabs which covered almost the entire length span of the composite specimens except for the area with impact-induced damage were used. However, the majority of thin specimens still experienced local crushing damage. It was determined that thin composite specimens of 2.24 mm were not suitable for use with the existing NASA's CAI test fixture.

EXPERIMENTAL RESULTS

By examining the force and energy histories, it was concluded that peak force, contact duration, and absorbed energy were the most important characteristics of composite laminates subjected to impact loading. Figs. 4-6 show the impact characteristics of both thick and thin laminates. The solid circles and open circles represent the characteristics for thick and thin composite laminates with effective impact zones of 125 mm x 125 mm, respectively. In addition, the dashed lines represent smooth curves of the solid circles while the solid lines represent smooth curves of the open circles in the diagrams. Fig. 4 reveals that the peak forces increase as the impact energy increases. However, the value becomes relatively stable for thick laminates and reaches a constant value for thin laminates. The turning points from nonlinear transition curves to stable or constant values are called critical points while the corresponding impact energy levels are called the *critical energy levels*. Similar results can also be seen from Fig. 6 for absorbed energy. In Fig. 5, the contact duration is presented as a function of the impact energy. For both thick and thin laminates, the contact duration increases rapidly as the impact energy increases. They reach individual peak points and sharply drop afterwards. The impact energy levels correspond to the peak points are also termed the critical energy levels.

1. PERFORATION THRESHOLDS

As mentioned above that perforation is the most apparent damage mode in composite laminates subjected to impact loading. Hence, the perforation threshold is an important parameter in characterizing the response of composite laminates subjected to impact loading [17-20]. Since the peak force, contact duration, and absorbed energy all reach critical points when perforation takes place and the impact energy levels to cause perforation match with the corresponding critical energy levels, the perforation threshold of composite laminates can be identified through the following four methods: peak force, contact duration, absorbed energy and equal energy.

A. Peak Force Method

In Fig. 4, the peak forces of thick composite laminates reach a relatively stable level, changing from a nonlinear transition curve to a straight line, around 16.2 kN when the impact energy is about 106 J, i.e. the critical energy level. This critical energy level was found to be slightly lower than the level to cause perforation by examining the impacted specimens. For thin composite laminates, the critical energy level is identified as 30 J and is associated with a plateau of peak force of 4.2 kN. By examining the impacted specimens, it was found that this critical energy level was slightly higher than the energy level that caused perforation in thin composite laminates. The plateau seems to indicate that there was a maximum contact force that a thin composite laminate can sustain when it was subjected to impact loading and the maximum contact force was what required to perforate the thin composite laminate.

B. Contact Duration Method

The second method to identify the perforation threshold was based on the contact duration. Fig. 5 shows the contact durations for thick and thin laminates at various impact energy levels. For thick composite laminates, the critical energy level is around 120 J while it is around 21.5 J for thin composite laminates. The former was very much the impact energy level to cause perforation since some thick specimens were perforated and some were not when subjected to this impact energy level. The latter was found to be slightly lower than that caused perforation since no thin specimens were perforated under this impact energy level.

C. Absorbed Energy Method

Shown in Fig. 6, the absorbed energy approaches a relatively stable level around 150 J for thick laminates when impact energy level reaches 190 J, i.e. the critical energy level. This impact energy level was much higher than that obtained from the peak force analysis as given in section 3.1 and was confirmed to greatly exceed the impact energy level to cause perforation. It should be pointed out, however, that there were relatively few data points located between 100 J and 200 J. It was believed that insufficient data points within the range were responsible for errors in generating a smooth curve, and hence the inaccurate estimate. The estimate of perforation threshold for 2.24 mm laminates is around 35 J when the absorbed energy reaches a constant level of 28.5 J. It was also higher than experimental observations.

D. Equal Energy Method

The fourth technique to identify the perforation threshold is based on comparison between impact energy and absorbed energy. It was found that composite laminates experienced perforation when these two energy levels became very close. In other words, perforation seemed to take place when the kinetic energy of the impactor was almost completely transferred to the composite laminate. Results based on this argument can be seen in Fig. 6. The 45° line which represents equality between impact energy and absorbed energy goes through solid circles and an open circle, giving the perforation threshold of 120 J for thick laminates and 26 J for thin laminates. These two results were found to best match with experimental observations for perforation threshold among the four methods.

2. RESIDUAL COMPRESSIVE PROPERTIES

In addition to nondestructive investigations, an effective way to characterize the degree of impact-induced damage is to quantify the residual properties of composite laminates which have been subjected to impact. It has been reported by many researchers that compression after impact is an effective test for this purpose due to the fact that delamination is an important damage mode in impacted composite laminates and compressive properties of composite laminates are very sensitive to the size and location of delamination.

Figs. 7-9 show the residual compressive stiffness, residual compressive maximum force, and residual compressive absorbed energy for thick composite laminates based on CAI tests. The *residual compressive stiffness* represents the slope of a force-displacement curve obtained from CAI test; the *residual compressive maximum force* represents the force to cause buckling, i.e. the peak force of the force-displacement relation; while the *residual compressive absorbed energy* can be calculated from the area under the force-displacement curve. The residual compressive stiffness decreases gradually as the impact energy increases. However, both the residual compressive maximum force and residual compressive absorbed energy drop rapidly from their initial values and become constants when the impact energy levels exceed individual critical levels. The critical energy levels were also identified to be closely related to the perforation threshold. This result indicates that a maximum mechanical properties degradation of composite laminates takes place at perforation. Once perforation takes place, some residual compressive properties of composite laminates cannot be further degraded. In other words, as far as the residual compressive maximum force and residual compressive absorbed energy are concerned, perforation seems to be the most important damage stage in composite laminates subjected to impact loading.

As impact energy increases, the reduction of residual compressive stiffness is not as dramatic as those of residual compressive maximum force and residual compressive absorbed energy. This is believed to be related to the fact that there is no delamination-induced local buckling involved in the measurement of compressive stiffness. In other words, local buckling plays a very important role in the reductions of residual compressive maximum force and residual compressive absorbed energy. Consequently, the residual compressive maximum force and the residual compressive absorbed energy are better than the residual compressive stiffness in presenting mechanical properties degradation of composite laminates subjected to impact loading. For convenience of discussions, the mechanical properties degradation will be referred to degradations of residual compressive maximum force and residual compressive absorbed energy hereafter.

As mentioned above, perforation took place when the residual compressive maximum force and residual compressive absorbed energy became constants as the impact energy approached critical values, changing from nonlinear curves to constants. The impact energy levels corresponding to the constant values of residual compressive maximum force and residual compressive absorbed energy, i.e. critical energy levels, for thick composite laminates are 115 J and 135 J, respectively. These two values are close to the impact energy level for perforation threshold, i.e. 120 J, as given in section 3.4. Accordingly, besides the aforementioned four methods, the studies of residual compressive maximum force and residual compressive absorbed energy present two additional options for estimating the perforation threshold.

The compression after impact testing was also performed for impacted thin composite laminates. Local crushing damage close to the top and bottom clamping ends occurred in many tests. Extra-long end tabs were used to reinforce the specimens' ends to prevent local crushing damage from happening. Unfortunately, among the very few specimens which had no local crushing damage, only a couple of them showed strong interaction between impact-induced damage and compression-induced damage. Hence, it was concluded that thin (2.24 mm) specimens are not suitable for CAI testing using NASA's test fixture.

DISCUSSIONS

1. SIZE EFFECTS

In this study, composite laminates of three effective impact zones and two thicknesses were investigated. However, the distinctions between the large and small, and the thick and thin laminates need to be further defined. According to the Classical Plate Theory, the definitions of thin and thick plates are tied to the ratio of in-plane dimension to thickness, . Table 2 gives the ratios of for all composite laminates investigated in this study. Since a ratio of 20 is usually considered as the minimum requirement for being qualified as a thin plate, 6.69 mm laminates are considered as thick plates. Although the thick specimens and the thin specimens have almost identical ratio, i.e. 18.7 and 18.8, respectively, experimental results between them were quite different. This indicates that the impactor diameter is also an important parameter in impact study.

The ratios of specimen in-plane dimension to impactor diameter, , and specimen thickness to impactor diameter, , are also shown in Table 2 along with the ratio of in-plane dimension to thickness . It can be seen from the ratios given in Table 2 that displays the equal important roles of in-plane dimensional and thickness effects, shows the sole important role of in-plane dimensional effect, while indicates the sole important role of thickness effect. Since experimental results show that thickness effect is much more significant than in- plane dimensional effect, seems to be the most important ratio among the three ratios presented. Since the impactor diameter is kept constant in this study, the thickness of composite laminates is then the most important parameter in impact response.

2. COMPARISON BETWEEN IN-PLANE DIMENSIONAL AND THICKNESS EFFECTS

The response of composite laminates to impact loading, to some extent, resembles plate bending which is governed by bending rigidity. The bending rigidity is defined as where is Young's modulus and is the second moment of area which can be expressed as where is laminate dimensions and is thickness. In fact, the bending rigidity has been successfully used in interpreting the potential of delamination in composite laminates subjected to impact loading [16]. The definition of the second moment of area shows that it is proportional to the third power of thickness while it is only the first power of in-plane dimension. Since the impact response of composite laminates as mentioned above is more strongly affected by thickness than by in-plane dimension, the bending rigidity, which is capable of discriminating between thickness and in-plane dimension, seems to qualify itself as an important element, if not the element, of an analytical model for perforation analysis.

The feasibility of utilizing bending rigidity in impact response analysis is also well supported by experimental results. As mentioned above, excellent linear relation of impact response exists when the impacted composite laminate is changed from single-layer to double-layer, and to triple-layer system. However, it is also found that the ratios of peak force and absorbed energy between thick and thin composite laminates are higher than the thickness ratio, exhibiting a nonlinear proportion with respect to thickness. Both of the results seem to provide a solid foundation of rationalizing the use of bending rigidity for perforation analysis.

3. DAMAGE MODES

Both the peak force and absorbed energy of impacted composite laminates reach relatively stable levels once perforation takes place. In addition, the residual compressive maximum force and residual compressive absorbed energy drop to constant values when perforation takes place. All these seem to imply that the peak force and absorbed energy should also become constant instead of just stabilized when perforation is reached. Hence, more tests are required to further verify this hypothesis. However, whether the impact response and mechanical properties degradation become constant or stabilized, the most significant fact is that they both reach apparent turning points when perforation takes place. Accordingly, as far as material response is concerned, perforation is the most important damage stage in composite laminates subjected to impact loading.

As mentioned above, the damage modes in perforated composite laminates includes macroscopic damage, such as indentation, surface cracking, delamination, and perforation, and microscopic damage, such as fiber breakage, matrix cracking, fiber-matrix debonding, etc. All individual damage modes play important roles in impact response of composite laminates. However, based on open hole study, it can be concluded that perforation alone causes a small portion of mechanical properties degradation. It is delamination which is responsible for local buckling and hence significant mechanical properties degradation.

Perforation is easy to identify. It is about the size of impactor. However, delamination area and location are very difficult to measure, if not impossible. Since delamination plays a very important role in impact response and mechanical properties degradation, many nondestructive techniques have been developed to identify delamination. In addition, it has been concluded that delamination cannot be represented by an equivalent hole size. It then is important to consider the true geometry of delamination, i.e. debonding between laminae, in delamination modeling.

4. CHARACTERISTICS OF PERFORATION AND DELAMINATION

The residual compressive stiffness is not strongly affected by delamination because local buckling does not occur in the early stage of a CAI test. In fact, it is dependent on a damage area combining the impactor and its surrounding area with through-the-thickness damage. Therefore, it is concluded that the modeling of compressive stiffness needs to be tied to the modeling of the through-the-thickness perforation zone. And a linear relation between the perforation opening and residual stiffness should be established.

The modeling of delamination can be approached from plate bending analysis. As a composite laminate bends, high interlaminar shear stresses are formed, resulting in delamination due to low interlaminar strengths. When the delaminated composite is subjected to uniaxial compression, local bending-buckling can take place in individual delaminated layers. Since bending rigidity decreases with the third power of thickness, as composites delaminates, both compressive maximum force and compressive absorbed energy degrade rapidly as delamination increases.

CONCLUSIONS

The following conclusions can be drawn from the investigations:

1. Once perforation takes place, both impact characteristics, such as peak force of impact, impact-contact duration and absorbed energy during impact, and mechanical properties degradation, such as residual compressive maximum force and residual compressive absorbed energy, reach turning points. Accordingly, these five parameters can be used to identify the perforation thresholds of composite laminates. Since these parameters are important elements of material response, perforation can be concluded as the most important damage stage, as far as material response is concerned, in composite laminates subjected to impact loading,
2. The study of size effects on impact response of composite laminates should be divided into two categories: in-plane dimensional effect and thickness effect. Among the ratios based on specimen in-plane dimensions, specimen thickness and impactor diameter, the ratio of specimen thickness to impactor diameter seems to best match with the experimental results. Since the impactor diameter is kept constant in this study, the thickness of composite laminates becomes the most important parameter in impact response. Hence, thickness effect is much more significant than in-plane dimensional effect.
3. In rationalize the superiority of thickness effect to in-plane dimensional effect on impact response, bending rigidity should be considered as an important element for perforation analysis since it is proportional to the third power of thickness while only the first power of in- plane dimension. Its capability of discriminating between thickness and in-plane dimension seems to be consistent with the experimental results that thickness effect is more significant than in- plane dimensional effect.
4. Although perforation is the most important damage stage, as far as material response is concerned, in composite laminates subjected to impact loading, perforation alone causes a small portion of mechanical properties degradation. It is delamination which also plays an important role in impact energy absorption and mechanical properties degradation since delamination has been identified as the other primary damage mode in impacted composite laminates.
5. The utilization of bending rigidity for perforation analysis can also be extended to delamination analysis. In fact bending rigidity has been successfully used in a previous study for predicting the potential of delamination of composite laminates subjected to impact loading. Its capability in interpreting the mechanical properties degradation is well supported by the experimental results that both compressive maximum force and compressive absorbed energy degrade rapidly when delamination exists while compressive stiffness does not.

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