Analysis of Charpy Impact Failure for Unidirectional Fiber-Reinforced Composite Laminates by Using a Computerized Fault Tree

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ABSTRACT

The fault tree analysis technique is one of systems approach techniques applied to analyze the Charpy impact failure modes of unidirectional fiber-reinforced composite laminates. It can define the processes leading to laminate failure under impact loadings. In order to perform a graphical analysis of the fault trees proposed here, two algorithms using a personal computer system are developed; one is an algorithm for obtaining the minimal cut sets and the other, for giving a color display of the paths leading to laminate failure by means of the computer system. As a result, it turns out based on Charpy impact data that there are 12 possible minimal cut sets which can cause typical failure modes such as the fiber pullout, the cleavage, the splitting, the delamination and the buckling at the compressive side of a specimen.

INTRODUCTION

The fact that the behavior under impact loadings for fiber-reinforced composite laminates is different from their static behavior has been pointed out by many investigators. Especially, it is emphasized that the impact properties do not depend upon matrix toughness but on the fiber stress-strain behavior (1). However, impact failure studies on composite materials have been carried out independently by many investigators for specified materials and testing methods. There is little attempt to make a systematic study on impact phenomena for composite laminates consisting of a variety of fibers and matrices. To make a systematic analysis of failure behavior in composite materials, the systems approach techniques are very useful regarding composite materials as so-called systems. The efficiency of systems analysis can be promoted by utilizing a personal computer system which is now available for structural analysis and design works on composite laminates (2).

In the present study, the fault tree analysis (FTA) technique, one of systems approach techniques will be adopted in order to achieve an understanding of the impact failure modes of fiber-reinforced composite laminates and to define the processes leading to laminate failure. An algorithm is also developed to carry out a graphical FTA using a personal computer system.

CHARPY IMPACT FAILURE MODES OF THE UNIDIRECTIONAL FIBER-REINFORCED COMPOSITE LAMINATES
It is well-known that the deformation behavior of materials depends on loading velocity or strain rate and its variation has much influence on their fracture strengths. Such a situation can be seen also in composite materials but their behaviors are not so simple as seen in single phase materials since there are considerable differences between the behaviors of fiber and matrix phases under the condition of high strain rate. Additionally, the relationships between stress and strain under static and impact conditions are different. In reality, composite materials may fail in several ways.

In order to analyze such complicated phenomena of composite laminates, an attention is paid to Charpy impact failure of fiber-reinforced composite laminates on which much data have been already reported. In many literatures concerning Charpy impact testing results on composite laminates, three papers (3-5) are selected, for Charpy impact failure of unidirectional advanced composites such as graphite/epoxy, Kevlar/epoxy and hybrids of the above two with glass/epoxy has been commonly discussed in detail and sufficient informations on failure modes and hybridization effects have been presented.

Based on these Charpy impact data, the typical failure modes of unidirectional fiber-reinforced composite laminates can be summarized as follows: (1) fiber pullout (Figure 1-a), (2) cleavage (Figure 1-b), (3) splitting (Figure 1-c) (4) delamination (Figure 1-d) and (5) buckling on the compressive side of specimen (Figure 1-e). Each of these figures is sketched with reference to the failure testing results of laminated specimens presented in the previous reports. In the following section, the processes leading to failure will be explained by the fault tree (FT) developed for Charpy impact failure modes of composite laminates.

FAULT TREE FOR EVALUATING CHARPY IMPACT FAILURE

Fault Tree Analysis For Composite Laminates

As mentioned in the previous sections, the composite material can be considered as a complex system since it consists of two phases of fiber and matrix. In fact, several mechanical models such as the weakest-link model, the parallel model, the dispersed model and others have been proposed by representing composite as a system to discuss the fracture behaviors. Therefore, the replacement of equipment or part failure by composite laminate failure allows us to study the fracture mechanism of composites from a viewpoint of systems analysis.

Masters et al. investigated qualitatively the tensile failure of fibrous laminated composites by using the FTA techniques (6).

Fault Tree Analysis Technique

The FTA technique was first developed at the Bell Telephone Laboratories for system evaluation and reliability assessment. In recent years, the FTA techniques coupled with the reliability theory has been successfully applied to structural safety analysis (7). The FT is the combination of the various possible events which are (or can be) linked with "Top event". Once the FT is described for the system even if it is large-scaled and complex, the failure of the whole system can be deductively analyzed by connecting all faults or events in the systems through a series of logic gates.

Construction of the Fault Tree

First, in order to construct the FT, the top event is defined as the impact failure of unidirectional fiber-reinforced composite laminate. The impact failure of the laminates considered here involves two phenomena of the physical separation of the laminate into two or more pieces and the excessive deformation, in such a circumstance under which we cannot use the laminates as structural members. Thus, these two events can be connected with the top event through 'OR' gate. The relationship among three events is illustrated in Figure 2-a, where the additional remarks such as T, F14 etc. for each event will be used in Boolean algebraic formulation of the FT discussed later. Secondly, the event "Separation" is connected to the lower portion as shown in Figure 2-b and can be characterized by fiber pullout or cleavage or either case accompanied with (abbreviated by aw) the delamination. On the other hand, the event "Excessive deformation" can occur macroscopically as delamination, splitting or buckling on the compressive side of specimen. (See Figure 2-c.) Moreover, every events follow a chain of events and
remaining portions of the FT are illustrated in Figure 3. Thus, the whole FT can be completed by connecting every transfer symbols. The conventional symbols which are illustrated in Figure 4 are used in making such connections.

DISCUSSIONS

Formulation of the Fault Tree by Using Boolean Mathematics

A minimal cut set can be generally defined as a collection of all the basic events, the undeveloped events and the modifiers which are necessary and sufficient to cause the system failure. In order to evaluate the minimal cut sets, we shall formulate the proposed FT by using Boolean mathematics. In Boolean mathematics, 'OR' gate in the FT denotes logically the union and 'AND' gate, the intersection. The FT as shown in Figure 2 can be expressed by the following equations:

\[
T = F_{14} + F_{15} \quad (1) \quad F_4 = B_1 \cdot G_2 + B_1 \cdot B_3 \quad (7)
\]

\[
F_{14} = G_5 \cdot F_2 + F_3 + F_5 + G_3 \cdot F_4 \quad (2) \quad F_6 = B_4 \cdot B_5 \cdot G_3 \quad (8)
\]

\[
F_{15} = F_6 + F_11 + F_{12} + F_{13} \quad (3) \quad F_{11} = U_2 \cdot R_{10} \quad (9)
\]

\[
F_3 = U_1 \cdot F_2 \quad (4) \quad F_{12} = U_4 \cdot R_{10} \quad (10)
\]

\[
F_5 = U_1 \cdot F_4 \quad (5) \quad F_{13} = B_7 \cdot B_8 \quad (11)
\]

\[
F_2 = B_1 \cdot B_2 \cdot G_1 \quad (6) \quad F_{10} = B_6 \cdot U_5 + U_3 \cdot G_4 \quad (12)
\]

Substitution of Equations (4) - (7) into Equation (2) yields

\[
F_{14} = B_1 \cdot B_2 \cdot G_1 \cdot G_5 + B_1 \cdot B_2 \cdot U_1 \cdot G_1 + B_1 \cdot U_1 \cdot G_2 + B_1 \cdot B_3 \cdot U_1 + B_1 \cdot B_2 \cdot G_5 + B_1 \cdot B_3 \cdot G_5
\]

\[
(1) \quad (ii) \quad (iii) \quad (iv) \quad (v) \quad (vi)
\]

Similarly, Equation (3) can be rewritten as follows;

\[
F_{15} = B_4 \cdot B_5 \cdot G_3 + B_6 \cdot U_2 \cdot U_5 + U_2 \cdot U_3 \cdot G_4 + B_6 \cdot U_4 + U_3 \cdot U_4 \cdot G_4 + B_7 \cdot B_8
\]

\[
(vii) \quad (viii) \quad (ix) \quad (x) \quad (xi) \quad (xii)
\]

Thus, the minimal cut sets can be obtained from the events involved in each term in Equations (13) and (14). It turns out that there 12 possible minimal cut sets which are listed as follows:

Separation

(i) Fiber overstressed, \( \varepsilon_f > \varepsilon_m \), Poor fiber/resin bonds, High interlaminar shear strength

(ii) Fiber overstressed, \( \varepsilon_f > \varepsilon_m \), Partial delamination, Poor fiber/resin bonds

(iii) Fiber overstressed, Partial delamination, Good fiber/resin bonds

(iv) Fiber overstressed, \( \varepsilon_f < \varepsilon_m \), Partial delamination

(v) Fiber overstressed, Good fiber/resin bonds, High interlaminar shear strength

(vi) Fiber overstressed, \( \varepsilon_f < \varepsilon_m \), High interlaminar shear strength

Excessive deformation

(vii) High modulus, High tensile and compressive strengths, Moderately high interlaminar shear strength

(viii) Overload, Partial fiber pullout, Relatively good interlaminar bonds

(ix) Partial fiber pullout, Improper fabrication, Load applied

(x) Overload, Partial cleavage, Relatively good interlaminar bonds

(xi) Improper fabrication, Partial cleavage, Load applied

(xii) Excessive bending stress, \( \sigma_c > \sigma_t \)
For example, from a minimal cut set (i) in this list, we can know that the physical separation can occur as a result of the intersection of the events, fiber overstressed, $f > f_c$, poor fiber/resin bonds and high interlaminar shear strength corresponding to the term of (i) in Equation (13) calculated by means of Boolean mathematics.

Application of a Personal Computer to the Fault Tree Analysis

When systems and the FT become more complicated and complex, we had better to utilize a computer to evaluate the FT systematically. In fact, Poucet presents a new methodology for the computer-aided FT construction and indicates that it can be a valuable tool for in-depth systems analysis (8). Then, computer algorithms are required to obtain the minimal cut sets. A personal computer system with a color display and mini floppy disks is expected to be an effective tool since it enables us to display the FT more easily and skillfully in a color screen and to analyze the minimal cut sets with aid of the symbolic logic.

As an example, the FT depicted in Figure 2-a, b and c are graphically generated on the color display as shown in Figure 5. The program runs on an NEC PC-8000 Series personal computer and is written in the BASIC language. Once the FT diagram is completely constructed, it can be stored in the mini-floppy disk. Thus, we can refer it easily whenever required. Figure 6 shows the flow chart of a computer algorithm to obtain the minimal cut sets, where the INITIAL subroutine involves the initialization of CRT display, setting of integer variables, initializing variables and others. The PRINT subroutine call causes to print out all minimal cut sets. As a result of the execution of this program, we obtained the minimal cut sets listed in Table 1, where -1 means True and 0, False. It should be noted that this result corresponds to the analytical result by means of Boolean mathematics. Moreover, if we demand the path determined under the given condition to be displayed in the specified color, then the program whose flow chart is illustrated in Figure 7 can meet such a requirement.

CONCLUSIONS

A systems approach has been presented for the analysis of impact failure modes of fiber-reinforced composite laminates by using the FT technique. The personal computer-oriented algorithms have been proposed to obtain the minimal cut sets and to generate graphically on a color display the path to be required in analysis. As a result, the path (minimal cut set) which will lead to failure could be obtained by interactive use of a computer. This will help us that we can recognize quickly the areas requiring further investigation when we make theoretical design and improvement of composite structures considering reliability assessment.

ACKNOWLEDGEMENT

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REFERENCES

Figure 1 Sketches for Impact Failure Modes

a Fiber pullout
b Cleavage
c Splitting
d Delamination
e Buckling on the compressive side of a specimen.

Figure 2-a FT(1) including the top event.

Figure 2-b FT(2) including event "Separation".
Figure 2-c FT(3) including event "Excessive deformation"

Figure 3-a "Fiber pullout"

Figure 3-b "Cleavage"

Figure 3-c "Splitting"
Figure 5 Examples of the FT illustrated on the color display using a personal computer.

Figure 7 Flow chart for giving a color display of the path determined under the given condition.
Table 1 List of minimal cut sets output from printer.

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Figure 6 Flow chart of an algorithm to obtain minimal cut sets written in the BASIC language.

a Main routine
b Subroutine ANALYSIS