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# NEW PROGRESS ON PREDICTION METHODOLOGY FOR RESIDUAL STRENGTH OF DAMAGED COMPOSITE LAMINATES IN ASRI

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**SUMMARY:** This paper summaries some achievements on prediction methodology for residual strength of damaged composites, particularly DI and FD failure criteria proposed by authors in ASRI during the past 10 years. The research survey on the prediction methodology for residual strength of damaged stiffened composite panels by means of FD criterion is presented briefly.

**KEYWORDS:** composite laminates, damage, residual strength, failure criteria, stiffened panels

## INTRODUCTION [1,2]

The types of defect/damage in composite laminates are much different from that in metal and the existence probability of defect/damage is much lager because of anisotropy, brittleness and nonhomogeneous of composite laminates, particularly the characteristic that their interlaminar properties are much lower than their intralaminar properties, and handly-layup and special deform processes utilized. It is necessary that the different types and sizes of holes (such as fastener holes) have to be induced into structures during the design process. Although they do not belong to manufacturing defect, they are usually considered as the subject of investigation on damage. During manufacturing, service and maintenance impact damage occurs very often by foreign objects with different energies in composite structures. Investigation and service experience showed that impact is the most threatened to structural safety among the above-mentioned types of defect/damage. Investigation showed also that the fatigue behavior of composite laminates is excellent and the static strength is more sensitive to notches. Usually the structural design can meet its fatigue life requirement as long as it meets the static strength requirement of the structure with defect/damage. The research on residual strength estimation methodology of composite laminates with defect/damage has been the key subject for many researchers in the world based on this background. This subject includes the following 4 cases, that is, specimens with a hole (a circular hole, an elliptic hole and a crack) under tension or compression, specimens with delamination(s) or impact damage under compression. So far for the specimens with a hole under tension more than 10 failure criteria were proposed since the end of the sixties of the 20th century, but only the average stress (AS) criterion and the point stress (PS) criterion are used more popularly for engineering estimation. Even for these criteria the so-called "material" constants $a_0$ and $d_0$ are actually not constant. For the specimens with a hole under compression only few papers could be found and the estimated results verified only by few test data. For the specimens with delamination(s) or impact damage under compression some papers have been published recently. The most of them utilized the assumptions of sublaminate buckling and softening inclusion and PS or some available failure criteria. All of them were verified by means of few test data and it is very difficult for them to be applied to engineering estimation. Recently based on a lot of test data Authors proposed Damage Influence (DI) failure criterion and Fiber breakage in Damage zone (FD) failure criterion, and the residual strength estimation methodology for the above-mentioned cases and damaged stiffened panels. All of these models were verified by as much as possible test data. The comparison showed that these criteria and models could apply to damage tolerance analysis for composite structures. The present paper summarized these achievements in Aircraft Strength Research Institute of China (ASRI).

## DAMAGE INFLUENCE (DI) FAILURE CRITERION AND FIBER BREAKAGE IN DAMAGE ZONE (FD) FAILURE CRITERION

### 1 Damage Influence (DI) failure criterion [3~5]

For avoid and overcome the limitation of previous characteristic-size-like failure criteria Tang X D et al performed numerical analysis for the available test data and their failure mechanisms and proposed Damage Influence (DI) failure criterion. Its main characteristics are the followings:

- Uniform expression for different types of damage and loading;
- Only one coefficient $\alpha$ dependent on the types of damage (hole, crack, delamination, impact etc) which is determined by unidirectional properties of the composite system without any special test);
- No definite damage boundary requirement for impact damage and the principle of "damage influence distance" was introduced in the criterion.

DI criterion can be described as that damaged laminates will fail when the weighted normal stress at the characteristic point near the notch (or damage) reaches the ultimate strength of undamaged laminates as the following expression

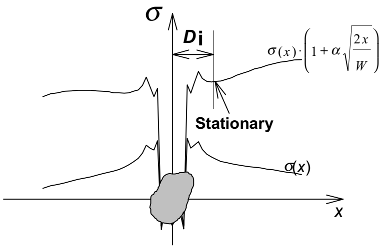


Fig 1 Damage influence distance $D_i$

$$\sigma(x)\left(1+\alpha\sqrt{2x/W}\right)\Big|_{x=D_i}=\sigma_b$$

$D_i$ is determined by $\frac{d}{dx}\left(\sigma(x)\left(1+\alpha\sqrt{2x/W}\right)\right)=0$

where $\sigma_0$ is the strength of the undamaged laminates (see Fig.1); $\sigma(x)$ is the normal stress distribution near damage; $W$ is the specimen width; $\alpha$ is the coefficient depend on the types of damage (hole, crack, delamination, impact damage etc.) and composite system properties. For the case of a circle hole under tension the expression of $\alpha$ is

$$\alpha=\left|\frac{A_{11}+A_{12}}{2A_{22}\left[1+(K_T^{\infty}-3)^2\right]}-\nu\right|+K_T^{\infty}\left(\sqrt{\left(\frac{2R}{W}\right)^3}-\left(\frac{2R}{W}\right)^2\right)$$

where $A_{ij}$ is the stiffness coefficients of the laminates; $\nu$ is Poison's ratio of the laminates; $K_T^{\infty}$ is the stress concentration factor. $R$ is the radius of the hole. | | denotes the absolute value.

For the case of delamination(s) or impact under compression the expression of $\alpha$ is

$$\alpha = \left[2\left(1 - t_{d\max}/h\right)\right]^{\left(1 - t_{d\max}/h\right)}$$

where *h is* the thickness of laminate; $t_{d\max}$ is the total thickness of sublaminates having the same stiffness reduction factor $R^{(j)}$ and are ordered continuously

$$R^{(j)} = \frac{N_X^{(j)} / t_j}{\sigma_0} = \frac{\sigma^{(j)}}{\sigma_0}$$

where $\sigma_0$ is the undamaged compression strength of the laminate; $N_X^{(j)}$ is the buckling load (per unit width) of the *j*th delaminated region (see Fig.2).

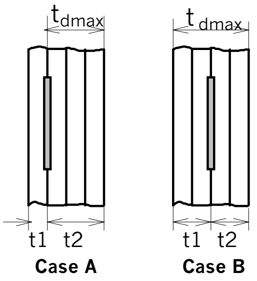


Fig.2 Calculation method of $t_{d\max}$

## 2 Fiber breakage in Damage zone (FD) failure criterion [6,7]

Chen P H et al observed the failure process of damaged composite laminates carefully and proposed the failure mechanisms assumption that a damage zone near the edge of the notch or damage occurs during loading process and the laminates will fail only when the fiber failure (breakage for tension, crinkling or wrinkling for compression) in the damage zone. Based on this assumption Chen P H et al proposed Fiber breakage in Damage zone (FD) failure criterion. Its main characteristics are the followings:

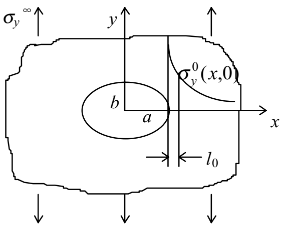


Fig.3 Normal stress distribution in 0° plies near the notch

- Uniform expression for different types of defect/damage and loading;
- Only one material constant — characteristic size $l_0$ determined by specimens with a hole under tension or compression;
- Characteristic size $l_0$ is independent of types of layups and configurations of specimens and dependent on loading types.

FD criterion can be described as that damaged laminates will fail when the average normal stress in the 0° plies of the laminates near the notch (or damage) over the characteristic size $l_0$ reaches the ultimate strength of the unidirectional laminates as the following expression

$$\frac{1}{l_0}\int_a^{a+l_0} \sigma_y^0(x,0)\,\mathrm{d}x = X_{\mathrm{t}} \ \ (\text{or } X_{\mathrm{c}})$$

or

$$\frac{1}{l_0}\left(\alpha_1 \int_a^{a+l_0} \sigma_x(x,0)dx + \alpha_2 \int_a^{a+l_0} \sigma_y(x,0)dx + \alpha_3 \int_a^{a+l_0} \tau_{xy}(x,0)dx\right) = X_{\mathrm{t}} \ \ (\text{or } X_{\mathrm{c}})$$

where $l_0$ is the material system constant; $a$ is the half length of the notch in $x$ coordinate direction; $\alpha_1$, $\alpha_2$ and $\alpha_3$ are laminate-related constants determined by classical laminate theory; $X_{\mathrm{t}}$ (or $X_{\mathrm{c}}$) is the longitudinal tension (or compression) strength of unidirectional laminates; $\sigma_y^0(x,0)$ is the normal stress distribution in 0° plies along the notch section in spite of damage zone (see Fig.3). The characteristic distances $l_0$ for widely-used composite systems are shown in Table 1.

Table 1 The characteristic size $l_0$ for different types of composite systems

| composite systems | | HT3/ 5405 | HT3/ QY8911-I | HT3/ 5222 | HT3/ KH304 | T300/ 914C | T300/ 5208 | AS4/ 3501-6 | AS4/ 3502 | AS4/ PEEK |
|---|---|---|---|---|---|---|---|---|---|---|
| $l_0$,mm | tension | 2.222 | 2.225 | 2.730 | 2.350 | 1.587 | 2.35 | 1.054 | 2.16 | 1.539 |
| | compression | 2.57 | 4.0 | 4.01 | 3.41 | 6.035 | | | 2.426 | w/2-a |

# PREDICTION METHODOLOGY FOR RESIDUAL STRENGTH OF DAMAGED COMPOSITE LAMINATES

## 1 Laminates with a hole

### 1.1 Tensile loading [3~7]

Both DI and FD failure criteria can be used for predicting the residual strength of laminates with a hole under tension. So far. the expression of $\alpha$ for the case of a circle hole is given out only for DI failure criterion. The normal stress distributions in 0° plies along the notch section of anisotropic plates with different types of thickness-through defect (including holes, elliptic holes and cracks) were derived out in ref. [6]. For the later the residual stress was predicted by means of FD failure criterion along with the corresponding characteristic size $l_0$. Test data from more than 10 composite systems, several decade layups, several hundred specimens are compared and the error is mostly less than 20% (see Fig.4 and Fig.5).

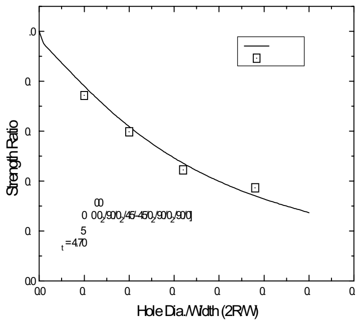


Fig.4 Comparison between test data and predictions based on DI

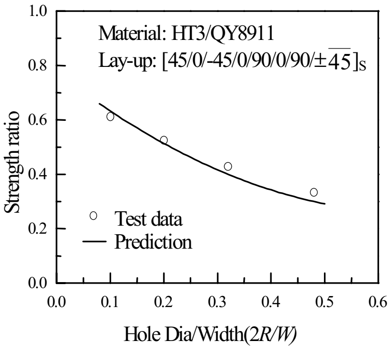


Fig.5 Comparison between test data and predictions based on FD

### 1.2 Compressive loading [6,7]

FD failure criteria can be used for predicting the residual strength of laminates with a hole (including circle and elliptic holes) under compression. The residual stress was predicted by means of FD failure criterion along with the corresponding characteristic size $l_0$. Test data from 5 composite systems, several decade specimens are compared and the error is mostly less than 20% (see Fig.6).

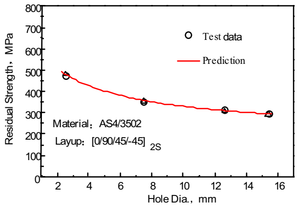


Fig.6 Comparison between test data and predictions based on FD

## 2 Laminates with delamination(s) under compression [3~5,7]

DI criterion and softening inclusion assumption can be used for predicting the residual strength of laminates with delamination(s) under compression. Test data from 4 composite systems, about 80 specimens are compared and the error is mostly less than 20%.

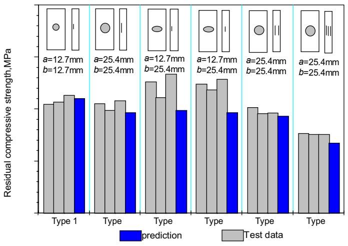


Fig.7 Comparison between test data and predictions based on DI

## 3 Laminates with impact damage under compression

This study can be divided into two parts, that is the estimation of impact damage and the residual strength estimation of laminates with impact damage under compression.

### 3.1 Estimation of impact damage

At first it is necessary to know the information about the shape, area and the distribution along the thickness of impact damage for analyzing the residual strength property of laminates after impact. It can be obtained by non-destructive inspection or predicted by means of analytical methods. For the later the key issue is the selection of the delamination criterion. Based on the theoretical analysis of delamination failure mechanisms Authors pressed the following two new delamination criteria.

#### 3.1.1 Bending Strain Energy Density (BSED) model [3~5]

Tang X D et al proposed the delamination criterion based on bending strain energy density according to the failure mechanisms of laminate spars. Its expression is

$$= \left( {}_{\mathrm{S}} / Y_{\mathrm{S}}^{*} \right)^2 + \left( {}_{\mathrm{M}} / Y_{\mathrm{M}}^{*} \right)^2 \geq 1$$

The main characteristic of this model is that no new physical parameter should be introduced except ordinary laminate properties and the “peanut” shape can be predicted.

#### 3.1.2 Shear Strain Energy Density (SSED) model [9]

Chai Y N proposed the delamination criterion based on BSED model and consideration on the action of lateral shear strength on delamination. Its expression is

$$e_{\mathrm{D}} = f_1 \left( \bar{\sigma}_2^{(\mathrm{L})} / Y^{(L)} \right)^2 + f_2 \left( \tau_{23}^{(U)} / S_{23}^{(U)} \right)^2 + f_3 \left( \tau_{31}^{(L)} / S_i \right)^2 \geq 1$$

This model can reflect the charicteristic of impact damage in thickness direction except the advantige of BSED model.

### 3.2 Prediction of residual strength under compression

There are two residual strength prediction methods proposed by Authors. More than 200 test data from 12 composite systems, 52 layups are compared with the predicted values by these two methods and the error mostly is less than 20%.

#### 3.2.1 Method based on DI criterion [3~5,7]

In this method the concept of Damage Data Structure (DDS) was utilized to characterize multi-modes of impact damage and different stiffness reduction modes were chosen for different failure modes and loading conditions. Impact damage was simplified as a softening inclusion zone. The computational steps are the followings.

- Measure or predict the impact damage, set up its Damage Data Structure (DDS) file;
- Calculate the stiffness reduction factor for each delemination region according to sublaminate buckling analysis; modify stiffness of each delamination area and report this modification to DDS file;
- (optional) If there are damage information such as fiber breakage or matrix cracking in the DDS, execute the appropriate stiffness reduction of the corresponding unit;
- Evaluate stress distribution after stiffness reduction of specimen by finite element method (FEM) or analytical method;
- Calculate the compressive strength by using DI failure criterion.

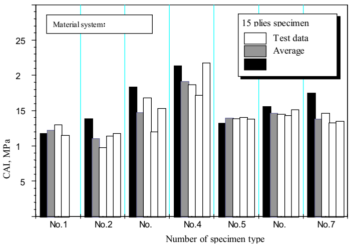


Fig.8 Comparison between test data and predictions based on DI

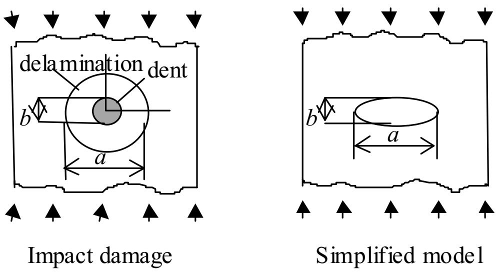
Based on this method CDTAC (Composite Damage Tolerance Analysis Code) software system [10] was developed in ASRI. Fig.8 is one of the computational examples.

3.2.2 Method based on FD criterion [6, 11]

In this method impact damage was simplified as an equivalent elliptic hole based on the experimental observation. The computational steps are the followings.

- Measure or predict the impact damage;
- Simplify the impact damage as an equivalent elliptical hole according to the principal;
- Calculate the normal stress distribution in 0° layers of the laminates near the elliptical hole by FE or complex stress function method;
- Calculate the compressive strength by using FD failure criterion.

Fig.10 is one of the computational examples.



Impact damage

Simplified model

Fig.9 The simplified model of impact damage

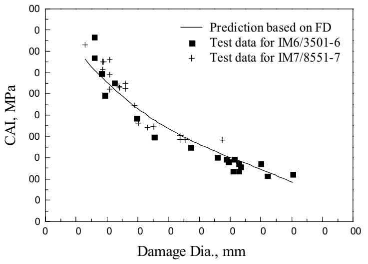


Fig.10 Comparison between test data and predictions based on FD

# METHODOLOGY FOR PREDICTING RESIDUAL STRENGTH OF DAMAGED COMPOSITE STIFFENED PANELS

## 1 Prediction of impact damage of stiffened panels [9]

As the same as the residual strength prediction of damaged laminates, it is necessary to know the information about impact damage for analyzing the residual strength property of stiffened panels after impact. Also it can be obtained by non-destructive inspection or predicted by means of analytical methods. The methodology used in ASRI is based on low-velocity impact transient response analysis of stiffened panels, FE method and SSED model.

## 2 Prediction of residual strength for stiffened panels with a crack (under tension) or impact damage (under compression) [12,13]

So far only few references on methodology on residual strength prediction for stiffened panels with a crack under tension were published. The new methodology on residual strength prediction for stiffened panels with a crack under tension and impact damage (including a hole) under compression was developed in ASRI. The computational steps are the followings.

- Calculate the normal stress distribution near the notch (crack, hole or elliptical hole simplified from impact damage) in the damaged stiffened panel by FE or rivet force method similar to the method developed for cracked metallic stiffened panels;
- Calculate the residual strength using FD failure criterion.

Test data from 73 panels are compared and the good agreement is obtained not only for residual strength, but also for initiation and arrest of damage propagation. The prediction results showed that no damage propagation arrest could occur for bonded and cocured stiffened panels and it was possible for damage propagation arrest to occur for closely mechanically-fastened stiffened panels. The conclusion was the same as the test results. Fig.11 and 12 are the comparison between test results and predictions for cracked stiffened panels under tension and stiffened panels with impact damage under compression, respectively.

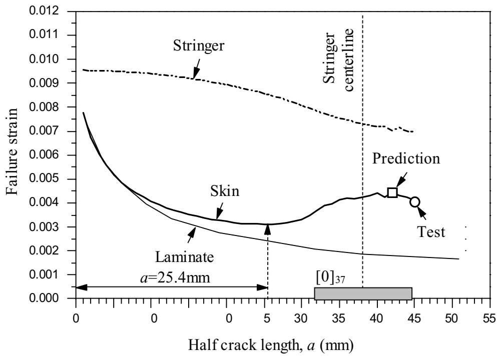


Fig.11 Comparisons between test data and predictions for T300/5208 Panels with a crack under tension

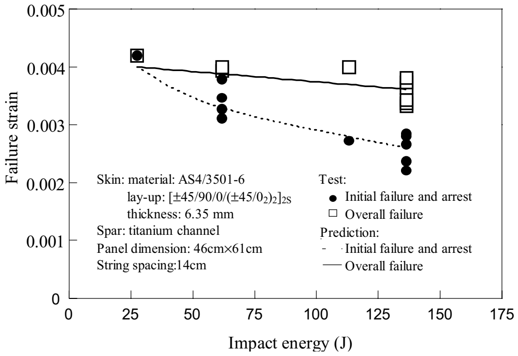


Fig.12 Comparisons between test data and predictions for AS4/3501-6 Panels with impact damage under compression

## CONCLUSION

Comparison of prediction methods of residual strength in ASRI and available methods is shown in Table 2 and 3.

Table 2 Comparison of prediction methods of residual strength in ASRI and available methods

| | **Condition** | | **Prediction method** | |
|---|---|---|---|---|
| | Damage type | Load condition | **ASRI** | Available |
| Laminates | Through-thickness notch (hole, crack) | Tension | DI(circular hole), FD | PSC, ASC, WEK…… |
| | | Compression | FD | ASC(?) |
| | Delamination | Compression | softening inclusion + DI | Sublaminate buckling + FM |
| | Impact damage | Compression | softening inclusion + DI, | softening inclusion + PSC, Max. Strain …… |
| | | | equivalent elliptical hole + FD | |
| | Impact damage | | BSED, SSED | Liu, Wu, …… |
| Stiffened panel | Through-thickness notch (hole, crack) | Tension | FD (including damage propagation) | Mar-Lin |
| | Impact damage | Compression | equivalent elliptical hole + FD (including damage propagation) | Non |
| | Impact damage | | SSED | Non |

Table 3 Comparison of prediction methods of residual strength in ASRI and available methods

| | **Condition** | | **Verification** | |
|---|---|---|---|---|
| | Damage type | Load condition | **ASRI** | Available |
| Laminates | Through-thickness notch (hole, crack) | Tension | Test data from more than 10 composite systems, several decade layups, several hundred specimens, the error is mostly less than 20% | The characteristic values in ASC,PSC,……are not material constants |
| | | Compression | Test data from 5 composite systems, several decade specimens<br>the error is mostly less than 20% | Only few test data |
| | Delamination | Compression | Test data from 4 composite systems, about 80 specimens, the error is mostly less than 20% | Only few test data |
| | Impact damage | Compression | Test data from 10 composite systems, 52 layups,<br>the error mostly is less than 20% | A few test data |
| | | | Test data from 10 composite systems, 52 layups are compared and the error is mostly less than 15% | |
| Stiffened panel | Through-thickness notch (hole, crack) | Tension | Test data from 2 composite systems, 19 specimens,<br>the error mostly is less than 15% | Only few test data |
| | Impact damage | Compression | Test data from 6 composite systems, 54 specimens,<br>the error mostly is less than 15% | Non |

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