TRANSIENT DYNAMIC ANALYSIS OF THE DAMAGE PROCESS OF LAMINATED COMPOSITE PANELS AND STIFFENED PANELS DUE TO LOW VELOCITY IMPACT

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Abstract A transient dynamic finite element analysis is presented for studying the damage process of laminated composite panels and stiffened panels due to low velocity impact. The analysis can be used to calculated displacements and transient stress and strain distributions of the panels, and the damage states in the panels during impact. An 20-node three dimensional super-element is developed in the analysis, and the Newmark scheme is adopted to perform time integration from step to step. An empirical contact law together with a new unloading law proposed in this paper is used to determine the impact contact forces between the projectiles and the panels. The variable interactive stiffness reduction method is carried out at the damaged plies in the elements to account for the local stiffness reduction of the damaged panels, and a modified impact induced delamination criterion is proposed and used in this analysis. The impact damage in terms of matrix cracking 、 delamination and fiberbreakage is concerned. The results of the analysis are compared with the existing test data, a good agreement is founded. Finally, the program developing in this paper is used for the analysis about the impact and damage process of the panel 、 the effect of the impact energy 、 the threshold energy of the impact damage, and the resistance of the stiffened panels to the impact damage etc.,and preliminary results are gained.

Introduction

A great deal of investigations have been done on the understanding of the process and damage characteristics of composite panels subjected to low velocity impacts. Among them, the effort of using finite element method to these research works seems very promising, for this method has the ability to treat with the vast variety of the material combinations 、 panel geometry 、 ply orientations 、 boundary conditions 、 and the material 、 mass 、 impact velocity of the projectiles, etc. The approach introduced by Reference[1] is a typical representation of this kind of works. It considered the normal displacement of the projectile to be a sum of two terms, they are the deflection of the panel and the local penetration. The first term is determined by the transient dynamic finite element method , the second term by the empirical contact law, which was proposed in Reference[2], for evaluating the contact force between the projectile and the impacted composite panel. The whole system, which is the combination of the motion of the projectile controlled by Newton's second law, and the panel, is then calculated by use of the Newmark time integration algorithm. The method above has been used for simulation the processes of the impact and the dynamic responses of the composite panels by many investigators, and has proved to be very successful.

However, because of the complexity of failure mechanism and the difficulties in mechanics, there seems to be no effective approach which can accurately predict the impact damage of the laminated composites. Recently in Reference[1], an new damage model was developed and failure criteria based on this model was used in the projectile-composite panel system for predicting the initiation of damage and the extent of the final damage in the composite panel. Although the damage predictions appear to agree well with the test data, they still did not consider the effect of the change of material properties caused by impact damage. This may result in errors in the simulation analysis process in two way, the stiffness reduction in the impact damage area and the effectiveness of the empirical contact law. So for more accurate predictions, the two aspects should be take into account.

In this paper, the algorithm is developed for simulating the impact responses and damage processes of the laminated composite panels and stiffened panels due to low velocity impact . It adopts a impact damage model for predict the initiation and propagation of the damage, and a variable interactive stiffness reduction method for considering the change of the constitutive relation of the damaged material. The empirical contact law proposed in Reference[2] is modified in this algorithm to suit for the serious damage condition. The algorithm has been put into practice through the transient dynamic finite element analysis method . The calculation results show that the prediction agree fairly well with the test data.

Dynamic finite element formulation

Finite element model

In order to consider the special mechanical characteristics of laminated composite, namely the mechanical inhomogeneity of reinforced materials and the presence of layers having different mechanical characteristics, the 20-node three dimensional super-element proposed in Reference[3] is adopted. This kind of elements has the ability to treat with many plies in one element. Because the material properties of the plies may be different through the thickness of the element, the element stiffness matrix must be calculated as

$$[K]_e = \iint \left\{ \sum_{n=1}^{n_T} \int_{X_{3(b)}^n}^{X_{3(t)}^n} [B]^T [D]_n [B] dx_3 \right\} dx1dx2 \quad (1)$$

where n_T is the number of piles in the element, $X_{3(t)}^n$、$X_{3(b)}^n$ are the x3 coordinates of the top and bottom of the nth ply, $[D]_n$ is the elasticity matrix of the nth ply.

Equations of motion

Following the standard finite element procedure, the finite element equations of motion of the impacted panel can be obtained

$$[M]\{U''(t)\} + [C]\{U'(t)\} + [K]\{U(t)\} = \{R(t)\} \quad (2)$$

where [M]、[C]、[K] are the mass、damping、and stiffness matrices, $\{U''(t)\}$、$\{U'(t)\}$、$\{U(t)\}$ are the acceleration、velocity、and displacement vectors, respectively. $\{F(t)\}$ is the force vector.
According to Newton's second law, the equation of motion of the projectile can be written as

$$m_p \cdot w_p''(t) + f = 0 \quad (3)$$

where m_p、$w_p''(t)$、 f are the mass、acceleration、and contact force of the projectile, respectively.
The Newmark time Integration scheme is adopted for solving the Equations(2) and (3) in this study. Thus, the above Equations can be written at each time step as

$$\overline{K}\{U(t+\theta\Delta t)\} = \{\overline{R}(t+\theta\Delta t)\} \quad (4)$$

where

$$[\overline{K}] = [K] + \frac{6}{(\theta\Delta t)^2}[M] + \frac{3}{\theta\Delta t}$$
$$\{\overline{R}(t+\theta\Delta t)\} = \{R(t)\} + \theta(\{R(t+\Delta t)\} - \{R(t)\})$$
$$+ [M]\left(\frac{6}{(\theta\Delta t)^2}\{U(t)\} + \frac{6}{\theta\Delta t}\{U'(t)\} + 2\{U''(t)\}\right) \quad (5)$$
$$+ [C]\left(\frac{3}{\theta\Delta t}\{U(t)\} + 2\{U'(t)\} + \frac{\theta\Delta t}{2}\{U''(t)\}\right)$$

and

$$m_p w_p(t+\theta\Delta t) = f(t+\theta\Delta t) \quad (6)$$

where

$$f(t+\theta\Delta t) = \frac{(\theta\Delta t)^2}{4} f(t) + m_p\left(w_p(t) + \theta\Delta t w_p'(t) + \frac{(\theta\Delta t)^2}{4} w_p''(t)\right) \quad (7)$$

Indentation law

To solve Equation(4) and (6) for determining the motion of the panel and projectile at time t+Δt, the contact force at that time must be known first. The empirical contact law proposed in Reference[2] can be used to solve the problem. The contact law are given as fellows

Loading: $$f = k\alpha^{1.5} \quad (8)$$

Unloading : $$f = f_m\left(\frac{\alpha - \alpha_0}{\alpha_m - \alpha_0}\right)^{2.5} \quad (9)$$

where α is indentation of the panel, k the contact constant, f_m.α_m is the maximum contact force just before unloading and the indentation corresponding to f_m, respectively. α_0 is the permanent indentation during the loading /unloading process.
Because the indention depth α is equal to the change of the distance between the center of the projectiles's nose and the mid-surface of the panel after they contact, the contact force at time t+Δt can be express through the displacements of Equation(4)、(6). As a consequence, the solving process can be continued. But when the impact energy is comparatively high, and the composite panel is seriously damaged, the empirical contact law may beyond its adaptive scope. In this case, the above empirical contact law should be discussed and revised.

Loading law

when the impacted panel is seriously damaged. the contract constant will change greatly. Although there is still no proper approach to determine the contact force according to the damage condition of the panel, the sensitivity of the contact constant to effecting the impact process can be investigated. Adopting the above contact law, the impact process of the $[45/0/-45/90]_{4s}$ graphite/epoxy panel with the dimension of 125mm × 75mm × 3.76mm, impacted by a 5kg projectile at the velocity of 1.41m/s is calculated. The result is showed in Figure 1. The contact constant getting the value of 1.41 × 10^9 N/m$^{1.5}$ [4] and the 0.437 × 10^9N/m$^{1.5}$, respectively. The latter may be considered the value when the composite panel is seriously damaged[5]. The changes of maximum contact force and the impact duration are within the scope of 5%. Accordingly, the change of the contact constant caused by the different extent of damage do not have much effect on the impact process, the loading law can still be used even at this condition.

The reason for this may be the interaction of the contact force、 the indentation、 the projectile displacement and the flexural displacement at the center of the panel during the impact process. For in the impact process, the decreasing(increasing) of the contact force caused by the decreasing(increasing) of the contact constant, will promote the increasing(decreasing) of the velocity and displacement of projectile and the decreasing(increasing) of the flexural displacement the center of the panel. This will result in the indentation increasing(decreasing) and will retard the decreasing(increasing) of the contact force in reverse. Therefore, the effects of the contact constant on the impact process are rather complicated. It is just the complicated interaction that make the effects of the contact constant on the impact process much less than that in the static contact problems.

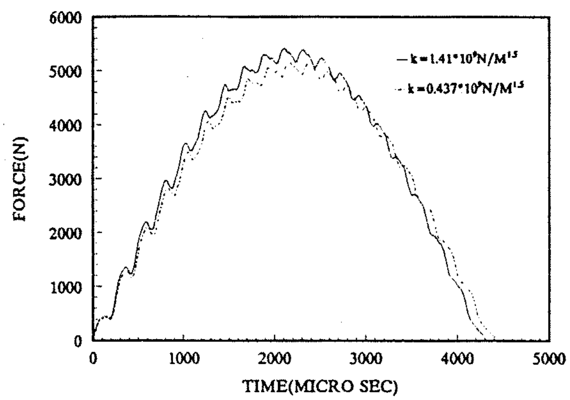

Figure 1. Contact forces with different contact constants

Unloading Law

For the unloading of the low velocity impact, there are two different types, i.e., the local unloading and the globe unloading , which should be distinguished. The former refers to as the temporary unloading caused by the dynamic response of the impacted panel during the nose of the projectile pressing into the panel, which can still be described by use of Equation(9)[5]. The latter refers to as the continual unloading during the projectile rebounding form the impacted panel.

During the global unloading process, The force between the projectile and the impacted panel will decrease as the decreasing of the flexural displacement at the center of the panel .For the undamaged panel, we obtain

$$f = f_m \frac{u}{u_m} \tag{10}$$

where f_m、 u_m are the contact force and the center flexural displacement of the panel at the beginning of the global unloading stage, respectively. At this time, the impact velocity of the projectile is zero. However, when the impact energy is comparatively high, the panel will be seriously damage, a notable dent usually appeares at the impacted surface of the panel, the relation of f and u is no longer keeps linear. In this case, an unloading law which is similar with Equation(9) in form is developed

$$f = f_m \left(\frac{u - d_0}{u_m - d_0} \right)^n \tag{11}$$

where d_0 is the depth of the residual dent after the impact. $n(n<1)$ is load factors. Both of them can be determined by the result of the experiment. According to the equation(11), there are $u=u_m$ and $f=f_m$ at the beginning of the global unloading; and $u=u_0$,and $f=0$ at the end of the impact process. In the process of global unloading , the relation of f and u can be adjusted by the load factor.

It should be noticed that d_0 and α_0 have different meaning, The permanent indentation α_0 is actually the change of the thickness of the composite panel at the impact point. When the panel is seriously damaged, the back surface of panel may be protruded. At this case, the value of d_0 is not equal to α_0, see Figure 2.

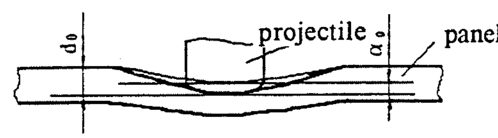

Figure 2. Schematics of the contact condition

Once the new unloading law, Equation(11), is put to use with the transient dynamic finite element method to simulate the impact and damage processes, the dynamic responses of the panel at the impacted place should be taken into account during the global unloading period , for the vibration of the panel can cause temporarily loading and make the impact load quiver as shown in experiment.

Damage model and failure criteria

The impact damage model developed in Reference[1] is adopted in this study. The model describes the damage mechanisms in laminated composite which is impacted as fellows:

(1) Intraply matrix cracks caused by transverse impact are the initial damage mode.

(2) Delaminations immediately initiate after the appearance of these matrix cracks, The delaminations are created from the cracks and can propagate into the nearby interfaces.
(3) Additional matrix cracks can occur subsequently in the other plies and can produce additional delaminations along the other interfaces.
According to this model, the failure criteria must have the function of prediction the initiation of the impact damage i.e. the critical matrix cracks, and the extent of the delaminations in the composites. The Tsai-Wu polynomial failure criterion is chosen for prediction the initiation of the impact damage in this study

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j = e_m \quad \begin{cases} e_m \geq 1 & \text{damage} \\ e_m < 1 & \text{undamage} \end{cases} \tag{12}$$

F_{ij} are defined as

$$\begin{aligned} &F_1 = 1/X_T - 1/X_C;\ F_2 = 1/Y_T - 1/Y_C;\ F_3 = 1/Z_T - 1/Z_C; \\ &F_{11} = 1/X_TX_C;\ F_{22} = 1/Y_TY_C;\ F_{33} = 1/Z_TZ_C; \\ &F_{44} = 1/R^2;\ F_{55} = 1/S^2;\ F_{66} = 1/T^2; \\ &F_{12} = -(4X_TX_CY_TY_C)^{1/2}; F_{13} = -(4X_TX_CZ_TZ_C)^{1/2}; \\ &F_{23} = -(4Y_TY_CZ_TZ_C)^{1/2} \end{aligned} \tag{13}$$

For predicting delaminaton creation and propagation, the failure criterion developed in Reference[5], which is the modified one of the criterion proposed in Reference[1]. is adopted:

$$\left(\frac{{}^{n+1}\bar{\sigma}_{33}}{Z_C}\right)^2 + D_S\frac{({}^{n}\bar{\sigma}_{23})^2 + ({}^{n+1}\bar{\sigma}_{13})^2}{S^2} + D_T\left(\frac{{}^{n+1}\bar{\sigma}_{22}}{Y}\right)^2 = e_D \quad \begin{cases} e_D \geq 1 & \text{damage} \\ e_D < 1 & \text{undamage} \\ {}^{n+1}\bar{\sigma}_{22} \geq 0 & Y = Y_T \\ {}^{n+1}\bar{\sigma}_{22} < & Y = Y_C \end{cases} \tag{14}$$

where, D_S . D_T are constant, they determine the effects of transverse shear stress and the bending tension stress on the delaminatons, respectively, and can be gained from impact experiment. The subscripts x 、 y 、 and z are the local material coordinates of an individual ply within the laminated panel, and the superscripts n and n+1 correspond to the upper and lower piles of the nth interface, and $\bar{\sigma}_{23}$ and $\bar{\sigma}_{22}$ are the averaged interlaminar and in-plane transverse stresses within the nth and n+1th ply, respectively. $\bar{\sigma}_{13}$ is the averaged interlaminar longitudinal stress within the n+1th ply.
Compared with the failure criterion in Reference[1], the first term in the left side of Equation(14) makes it possible to predict the damage caused by impact compress stress just under the projectile nose. This term may play an important role when the impacted composite panel is very thick, and the initiation of the damage is caused by the impact compress stress. In addition, the effects of ply orientations on the delaminations are included in the constants D_T . D_B, This make Equation(14) more simple, and easy to use, but it also restrict the scope of its usage. Theoretically speaking , Equation(14) is only suitable for the Quasi-isotropic laminated composites. But in practice application, Equation(14) has been used for ordinary laminated composite panels, which have the material properties closed to Quasi-isotropic in Reference[5], and does not cause much error compared with the results of experiments.

Stiffness reduction and damage process simulation

The initiation and propagation of the damage in laminated composite panel during the low velocity impact is a progressive process. To simulating this type of damage, the stiffness reduction method should be adopted for considering the effects of the damage of material on the impact process and the damage propagation. The algorithm in this study is described as fellow:
(1) Compute the stress at each gauss point in plies of each element at t_i time step.
(2) Check whether any of the gauss points have failed by applying the Equation(12). If no damage takes place, go to step 5, otherwise, the initial damage may take place, the stiffness properties of the damage plies are reduced as fellow[6]

$$\begin{aligned} &E_2^{1D} = SRC \cdot E_2; G_{23}^{1D} = SRC \cdot G_{23}; G_{12}^{1D} = SRC \cdot G_{12}; \\ &\gamma_{21}^{1D} = SRC \cdot \gamma_{21};\ \gamma_{23}^{1D} = SRC \cdot \gamma_{23} \end{aligned} \tag{14}$$

where '1D' means the constant that has been modified one time after the damage of the material. SRC is the stiffness reduction coefficient, it can only be determined by calculating test.
(3) Check whether any of the gauss points in the plies which have initial damage and their adjacent plies have failed by applying Equaion(14), determine the extent of the delaminations and reduce the stiffness properties within the extent[6]

$$\begin{aligned} &E_3^{1D} = SRC \cdot E_3; G_{23}^{1D} = SRC \cdot G_{23}; G_{13}^{1D} = SRC \cdot G_{13}; \\ &\gamma_{31}^{1D} = SRC \cdot \gamma_{31};\ \gamma_{32}^{1D} = SRC \cdot \gamma_{32} \end{aligned} \tag{15}$$

Meanwhile, if the stress at any gauss points satisfies the following maximum stress criterion[7]

$$\sigma_1 \geq X_T \tag{16}$$

then it is believed that the fibers at the gauss points are broken, the stiffness properties of the plies which contains the gauss points should be reduced[6]

$$E_1^{1D} = SRC \cdot E_1; G_{13}^{1D} = SRC \cdot G_{13}; G_{12}^{1D} = SRC \cdot G_{12};$$
$$\gamma_{13}^{2D} = SRC \cdot \gamma_{13}^{1D}; \gamma_{12}^{2D} = SRC \cdot \gamma_{12}^{1D} \quad (17)$$

(4) Recreate the stiffness matrix by use of the reduced stiffness properties, and go to step1 again.

(5) Compute the stress at t_{i+1} time step, and check whether any other places, which do not damage this time step before, have failed by applying the Equation(12).The new damaged places are treated as (2)~(4). Meanwhile check the places which have already damaged before, by applying the Equation(12)、(14)、(16). When the further damage takes place again. Reduce their stiffness properties as fellow:

for matrix cracking:

$$E_2^{2D} = SRC \cdot E_2^{1D}; G_{23}^{2D} = SRC \cdot G_{23}^{1D}; G_{12}^{2D} = SRC \cdot G_{12}^{1D};$$
$$\gamma_{21}^{2D} = SRC \cdot \gamma_{21}^{1D}; \gamma_{23}^{2D} = SRC \cdot \gamma_{23}^{1D} \quad (18)$$

for delemination:

$$E_3^{2D} = SRC \cdot E_3^{1D}; G_{23}^{2D} = SRC \cdot G_{23}^{1D}; G_{13}^{2D} = SRC \cdot G_{13}^{1D};$$
$$\gamma_{31}^{2D} = SRC \cdot \gamma_{31}^{1D}; \ \gamma_{32}^{2D} = SRC \cdot \gamma_{32}^{1D} \quad (19)$$

for fiberbreakage:

$$E_1^{2D} = SRC \cdot E_1^{1}; \ G_{13}^{2D} = SRC \cdot G_{13}^{1D} \quad G_{12}^{2D} = SRC \cdot G_{12}^{1D}$$
$$\gamma_{13}^{2d} = SRC \cdot \gamma_{13}^{1D}; \ \gamma_{12}^{2D} = SRC \cdot \gamma_{12}^{1D} \quad (20)$$

(6) Repeat(4), whenever the damage takes place, the corresponding stiffness properties will be reduced, until the impact damage process is over.

Numerical result and discussion

T300.QY8911 composite is selected for this study. The material properties given in Reference[7] are listed in table 1. The dimension of the $[45/0/\text{-}45/90]_{4s}$ panel is 125mm × 75mm × 3.76mm, and is simple supported at its four edges. The four corners of the panel are also clamped to simulate the real support condition in the impact experiments. The dimension of stiffened panel is given in Figure 3. The ply orientations of the panel are $[45/0/\text{-}45/90]_9$, and the stiffeners are made of 0 degree fibers, which is parallel to the length direction of them. The stiffened panel is clamped at its two opposite edges, which are perpendicular to the stiffener. The finite element meshes used for the calculations are presented in Figure 4、Figure 5.

Table 1. Material Properties of T300/QY8911 Used for Calculation

E_1(GPa)	135	X_T(MPa)	1548
E_2(GPa)	8.8	X_C(MPa)	1226
E_3(GPa)	8.8	Y_T(MPa)	55.5
G_1(GPa)	4.5	Y_c(MPa)	218
G_2(GPa)	4.5	Z_T(MPa)	55.5
G_3(GPa)	4.5	Z_C(MPa)	218
γ_{23}	0.33	S_{12}(MPa)	89.9
γ_{31}	0.33	S_{31}(MPa)	89.9
γ_{21}	0.33	S_{23}(MPa)	89.9
ρ (kg/m^3)	1614		

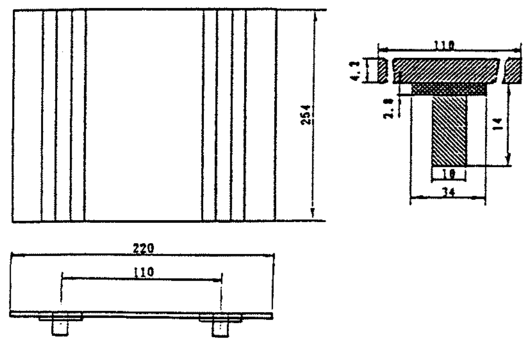

Figure 3. Dimension of the stiffened panel

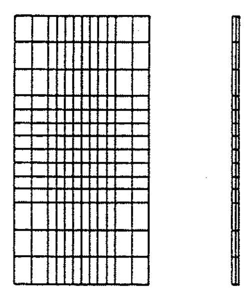

Figure 4. Finite element mesh for unstiffened panel

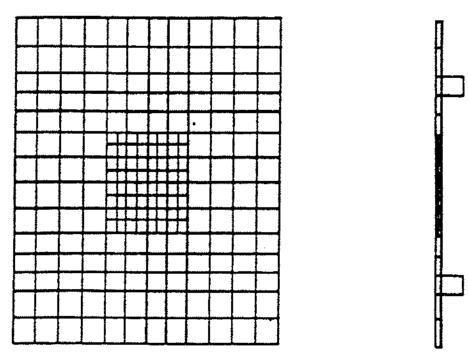

Figure 5. Finite element mesh for stiffened panel

The mass of the projectile is assumed to be 5 kg. The load factor is getting the value of 2.5 at anytime according to our calculation tests. The permanent indention α_0 is 1.5mm $\times$ 2.5mm $\times$ 4.0mm for the panel with the impact energy of 17.8J 、 26.7J 、 55J. And 2.0mm for the stiffened panel with 55J. respectively. The contact constant used in this study is 1.41 $\times$ $10^9 N/M^{1.5}$[4] , for the spherical steel nose head with radius of 6.25mm The SRC is 0.6 and the D_S 、 D_T are getting the values of 7.2 、 1.2[5], respectively.

The convergence of the finite element mesh and stability of the time integration are tested. It has been showed that for the mesh in Figure 4 、 Figure 5 the time integration step Δt=1.0 microsecond would lend to a converged solution. In the present study, Δt=0.5 microsecond is chosen.

According to the simulation results, which agree fairly well with the test data[5](Figure 6 、 Figure 11 、 Figure 12), several preliminary discussions can be made as follows:

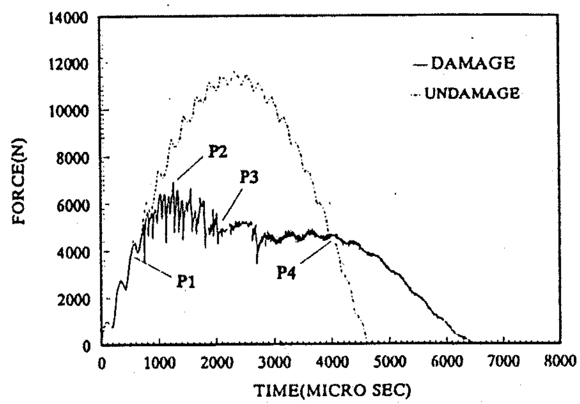

Figure 6. Contact force history

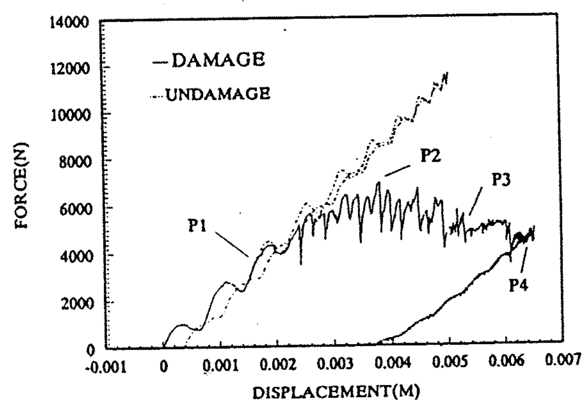

Figure 7. Contact force versus FDCP

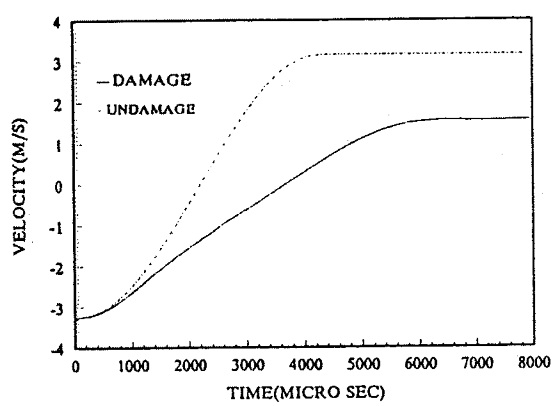

Figure 8. Impact velocity of the projectile

Typical impact process

The typical impact damage process of composite panels can be divided into five stages:

(1) From the beginning of the impact to P1 The impact force and the flexural displacement at the center of the panel(FDCP) increase rapidly. But the curves change fairly, the regular undulations of the curve are caused by the dynamic effecting of the impacted panel(Figure 6 、 Figure 7). In this stage, the curves of impact force 、 FDCP 、 impact velocity and change of kinetic energy of the projectile are all coincident with the corresponding curves of the impact process which does not take the impact damage into account in the calculation. This means that the stiffness of the impacted panel is not changed obviously(Figure 6 ~ Figure 9). At the point P1, slight damage in the form of matrix cracking and delamination have just appeared, so P1 can be regarded as the initial point of the impact damage(Figure 10).

(2) From P1 to P2 The impact force reaches its maximum at the point P2, but the increasing rate is lower than the first stage. As the impact process going on, the intensive random fluctuation of the impact force arises, and the curves of the impact force 、 FDCP 、 impact velocity and kinetic energy change are deviated from the curves which do not consider the effects of damage (Figure 6 ~ Figure 9). This phenomenon is caused by the change of stiffness of the damaged panel. At this stage, the impact damage develops rapidly, and at point P2, there has been extensive damage in the panel(Figure 10).

(3) From P2 to P3 With high amplitude fluctuation, the impact force begin to decrease from point P2 to point P3(Figure 6). Meanwhile, the FDCP continue to increase appreciably(Figure 7), this demonstrates that the stiffness at impact place is still losing rapidly, and the impact

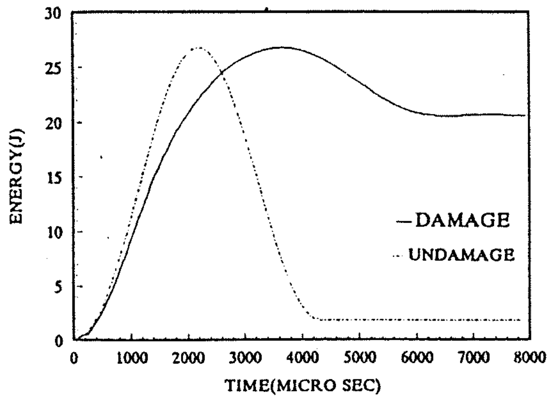

Figure 9. Variety of the kinetic energy of the projectile

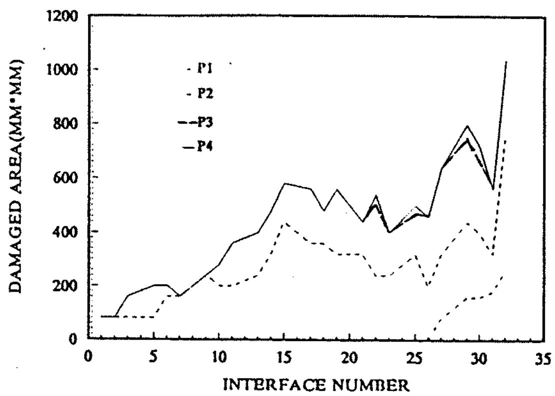

Figure 10. Damage condition for different stages

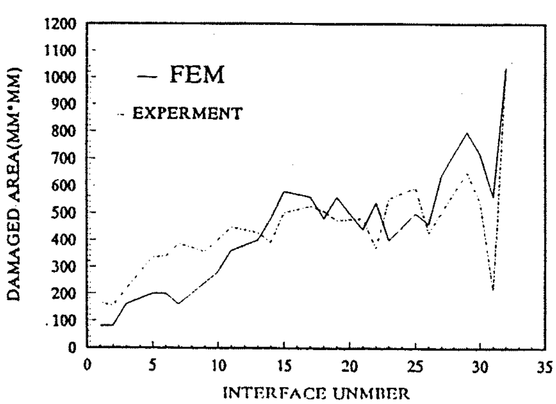

Figure 11. Damage condition for FEM and experiment

damage is also developing. At Point P3, the damage area is almost reaching its maximum(Figure 10).

(4) From P3 to P4 The impact force goes into the stable stage, the change of it is small, the amplitude of the random fluctuation is decreased, but the projectile is still in pressing state until the impact process reach point P4, the velocity of the projectile is zero(Figure 6 、 Figure 7). This means the damage in the panel has been developing in this stage. As the impact damage area almost ceases extending (Figure 10), the damage may mainly manifests itself as the intensifying of damage degree. At this time, the damage of the panel not only has the form of matrix cracking and delamination, but also has some fiberbreakage.

(5) Form P4 to the end of the impact This is the last stage of impact process. The impact force begins to decrease, the amplitude of the random fluctuation is small, and motion of the impacted panel and the projectile is all in their rebounding state(Figure 6. ~ Figure 8.). Because the impact place of the panel is seriously damaged, its stiffness is decreased heavily, this makes the rebounding force acting on the projectile rather small, and the increasing of velocity of the projectile slowly. Until the impact force is zero, the projectile leaves the panel at rather lower velocity compared with the velocity at the beginning of the impact(Figure 8). The loss of the kinetic energy of the projectile has absorbed by the damage of composite panel(Figure 9).

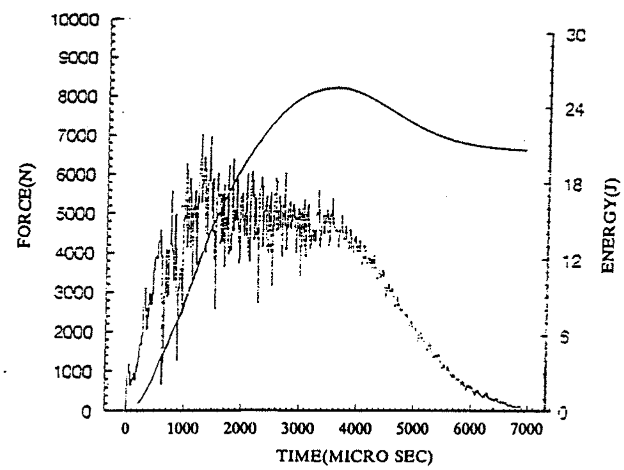

Figure 12. Experiment contact force history

<u>Effect of impact energy</u>

When the impact energy is high enough to create some extent damage in the composite panels, the characteristics of the impact and damage process are similar. They all have five stages as mentioned above, the variation of the impact energy only effects the stage 4 appreciably(Figure 6 、 Figure 13 、 Figure 14). This means when the impact energy reaches to a certain value, for example 26.7J in this study, the increasing of the

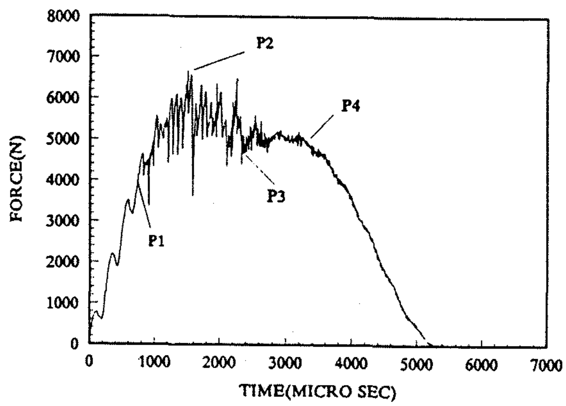

Figure 13. Contact force for 17.8J impact energy

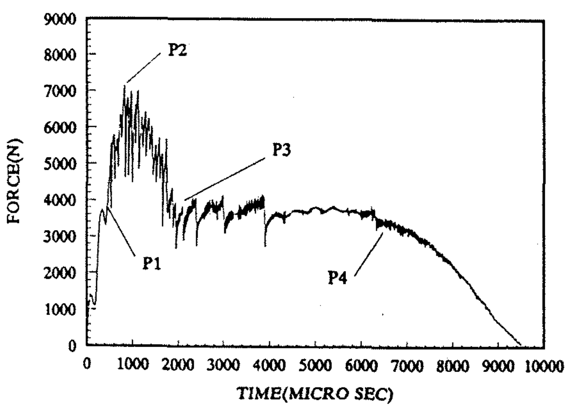

Figure 14. Contact force for 55J impact energy

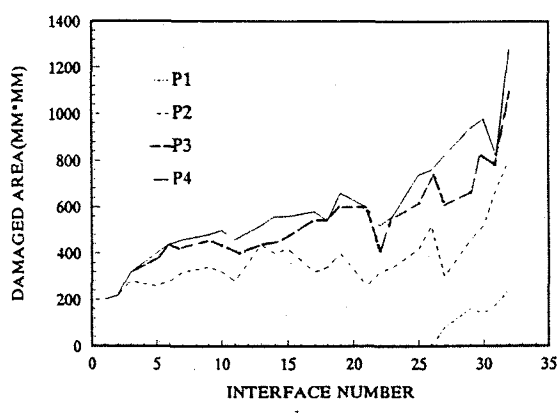

Figure 15. Damage condition for 55J impact energy

impact energy can not results in the increasing of damage area in large quantities(Figure 15), for the developing of the damage area is very slow after stage 3(Figure 10). But as the energy increases, the stage 4 of the impact process is lengthened, the degree of the impact damage may be intensified, until the impact energy is high enough to punctured the composite panel.

Threshold energy

To investigate the characteristics of the threshold energy, several kinds of laminated panels with the same ply configuration $[45/0/\text{-}45/90]_{ns}$ but different thickness are studied(Fig. 14). The results show that the thickness of the panels has great effect on the impact damage threshold energy. For relatively thin panel(n=4), the threshold energy is below 5J. The initial damage is in the form of matrix cracking and delamination in the panel near the back surface, because in this case, the flexural stiffness of the panel is small. The damage is first created by the bending tension stress. As the thickness increase(n=16), the effect of the bending stress becomes comparatively small and the effect of transverse shear stress becomes important, at this time, the threshold energy increase rapidly, and the form of the initial damage is matrix cracking and delamination mainly in the middle place of the panel. When the thickness of the panels is thick enough(n=24 ~ 28), the threshold energy may reach its not much effect on the threshold energy , the initial damage is the compressing damage just under the nose of the projective.
maximum, on the occasion, the thickness of the panel as

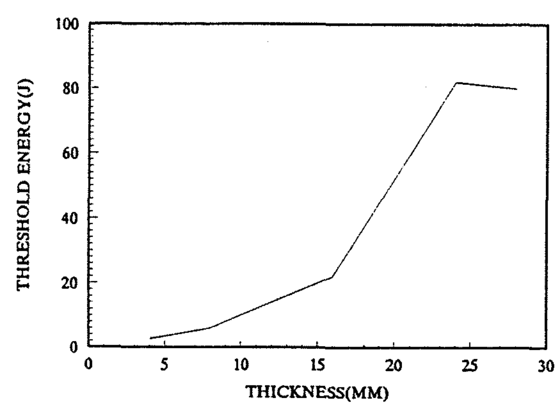

Figure 16. threshold energy versus thickness

Characteristics of the stiffened panel

Because existence of the stiffeners, the characteristics of the impact damage of the stiffened panels are very different from the unstiffened panels. The stiffeners raise the flexural stiffness, especially, they change the position of the neutral axes of the panels making them closer to the back surface. These factors improve the resistance of the stiffened panels to the impact damage:

(1) For the characteristics of the stiffened panels above, the creation of the initial damage near the back surface of the impacted panels needs higher impact energy. This means the threshold energy for the stiffened panels with ordinary thickness will be increased compared with the unstiffened panels.

(2) For the same reasons, the distribution of the impact damage in each interface of the stiffened panels turns to be more uniform than the unstiffened panels, and the damage projective area is comparative small(Figure 18). This decreases the loss of the stiffness of the panel, and lead to the impact force in stage 4 relatively higher as compared with the unstiffened panel(Figure 17). More important, This kind of damage area distribution can improve the residual compressive strength greatly[5].

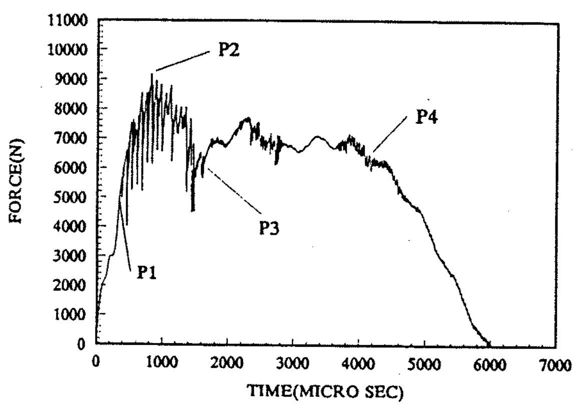

Fig.17 impact force for stiffened panel

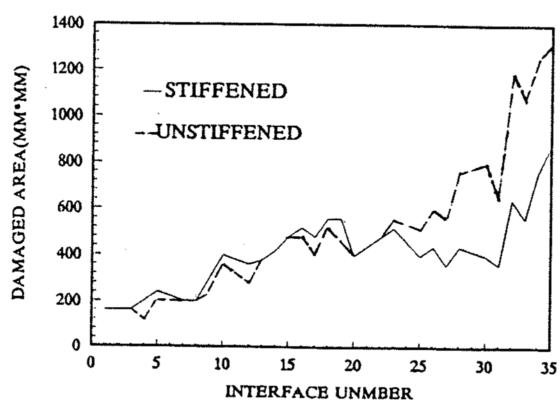

Figure 18. Damage condition for stiffened panel and unstiffened panel

Conclusion

A study is performed on the impact histories and damage characteristics of laminated composite panels and stiffened panels due to low velocity impact. A transient dynamic finite element analysis program APIC is developed for this study. Adopting the modified contact law and failure criterion, the code can simulate the impact behavior of the projectiles and panels, including the damage process in the panels accurately.

The results of the numerical simulations show that the impact histories can be divided into five stages, the impact damage is mainly developed in the second and the third stage, and the fourth stage changes more sensitive to the variation of the impact energy. It is also shown that there exists an impact damage threshold energy. When the impact energy is above the threshold, impact damage will be occurred, the threshold value and the position of the initial damage are mainly dependent on the thickness of the panels. For stiffened panels, the stiffeners have important effect on the impact damage behavior, they reduce the area of the damage and change the damage distributions in the panels, these make the stiffened panels maintain higher compression residual strength than the unstiffened panels.

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