Projectiles Impact Assessment of Aircraft Wing Structures with Real Dynamic Load

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Abstract. This paper presents an analysis to achieve the impact damage of the wing structure under real dynamic load. MPCCI tools are utilized to convert wing aerodynamic load into structural Finite Element Method (FEM) node load. The ANSYS/LS-DYNA code is also used to simulate the dynamic loading effects of the wing structure hit by several projectiles, including both active damage mechanism and common damage mechanism. In addition, structural node force on the leading edge and the midline is compared to the aerodynamic load separately. Furthermore, the statistical analysis of the penetrating size and the stress concentration around the damage holes indicates that under the same load situation, the structural damage efficiency of active damage mechanism is significantly higher than the one of common damage mechanism.

1. Introduction
Experimental and numerical studies have been carried over the past few years in order to evaluate the impact damage of aircraft structures. Aircraft damage assessment, especially the damage under projectiles impact has become a non-ignorable part of aircraft vulnerability analysis and high survivability design. The aircraft will suffer the aerodynamic load and impacting load during different flight phases of a mission, the assessment of aircraft damage becomes more complicated under this coupling effect. The aerodynamic characteristics analysis and combat process are considered separately in current research: Garcia-Castillo S K [1] evaluated the ballistic limits of aluminium alloy under normal impact of spherical steel projectiles, when they are subjected to uniaxial in-plane. F R Ahad[2] simulated the failure of aluminium alloy under high velocity impact. J Donea[3] provided an arbitrary Lagrangian-Eulerian kinematical description of the fluid domain in which the grid points can be displaced independently of the fluid motion. C Farhat and M Lesoinne[4] presented a new algorithms for converting the fluid pressure and stress fields at the fluid/structure interface into a structural load, and for transferring the structural motion to the fluid system. Therefore, it is meaningful and necessary to do some research to take the aerodynamic loading and impact loading into consideration in wing structure damage assessment.

The different types of threats that an aircraft is faced with during flight mission can be divided into common damage mechanism and active damage mechanism due to their killing mechanisms. The common damage mechanism is non-explosive penetrating projectile while the active mechanism is the multifunctional structural fragment[5] with energetic material which was presented in the last century.
When collision happens, rapid chemical reaction occurs in the internal energetic material because of the strong impact, releasing a certain amount of energy, even burning at the same time. Due to the aftermath explosion and burning, the damage efficiency is significantly enhanced\(^6\).

In this paper, the research of damage efficiency of active damage mechanism is aimed at the explosive active damage mechanism. The damage efficiency is blasting and energy output which is mainly represented by shock wave. Different from common damage mechanism, most of the present active damage mechanism are explosions that coated with inert high strength metal shell due to the launching conditions and terminal damage effect and the active damage mechanism researched in this paper is a cylinder projectile with a hemisphere head.

The analysis of common and active damage mechanisms are conducted and compared respectively, section 2 introduces the material model and the state equations used in the simulation model; section 3 gives a detailed introduction of the modelling method and information; in section 4, the dynamic response is analysed after the aerodynamic load is transformed into structural load by the MPCCI tools; section 5 assumes that wing structure is hit by two rows of ten stars of the projectile, and simulates its injury condition.

2. Calculation Methods

Both the common damage mechanism and the shell of the active damage mechanism are modelled by 45\(^9\) steel with JOHNSON-COOK\(^7\) material model and GRUNEISEN equation of state. The internal explosive material model and equation state of active damage mechanism are respectively chosen as *ELASTIC-PLASTIC-HYDRO and *IGNITION-GROWTH-OF-REACTION-IN-HE; The wing structure uses the *MAT-PLASTIC-KINEMATIC material model and *EOS-LINEAR-POLYNOMIAL equation of state.

2.1.1. JOHNSON-COOK model

Johnson and Cook presented this suitable constitutive model of large deformation, high strain rate and high temperature conditions for metal material. Due to its simple form and convenient use, this material model is widely used for the study on metal impact mechanics. The yield stress is expressed by equation (1) in this model:

\[ \sigma_y = (A + B \varepsilon^p_m)(1 + c \ln \varepsilon^*)(1 - T^m) \]  

where \(A\), \(B\), \(c\), \(n\), \(m\) are material parameters determined by experiment, \(\varepsilon^p_m\) is the effective plastic strain, \(T^m\) is the homologous temperature.

\[ \varepsilon^* = \varepsilon^p \varepsilon_0^{-1} \]  

\[ T^m = (T - T_{room})(T_{melt} - T_{room})^{-1} \]  

\(T_{room}\) is the room temperature, \(T_{melt}\) is the melt temperature of the material.

2.1.2. GRUNEISEN equation of state

The Gruneisen equation of state with cubic shock velocity-particle velocity defines pressure for compressed materials as:

\[ p = \rho_0 C^2 \mu [1 + \left(1 - \frac{\gamma_0}{2}\right) \mu - \frac{a}{2} \mu^2 \left(\frac{\mu}{\mu + 1}\right)^3] \left[1 - \left(S_1 - 1\right) \mu - S_2 \frac{\mu^2}{\mu + 1} - S_3 \left(\frac{\mu}{\mu + 1}\right)^2\right] + (\gamma_0 + a \mu) \rho_0 \]  

where \(C\) is the intercept of the Vs-Vp curve; \(S_1\), \(S_2\), and \(S_3\) are the coefficients of the slope of the Vs-Vp curve; \(\gamma_0\) is the Gruneisen gamma; \(a\) is the first order volume correction to \(\gamma_0\); and \(\mu = \rho \rho_0^{-1} - 1\).
2.1.3. *IGNITION-GROWTH-OF-REACTION-IN-HE model
The *IGNITION-GROWTH-OF-REACTION-IN-HE model, presented by Wackerle and Johnson\cite{8} in 1976, was used to simulate the shock ignition (or ignition failure) and the shock wave propagation of solid explosive. This three-ignition growth model based on hot-hole collapse mechanism which was corrected by Lee and Tarver, and then developed into the complete IGNITION-GROWTH-OF-REACTION-IN-HE model, it is the so called Lee-Tarver model. It is mainly used to calculate the explosive shock reaction conditions from start to finish. It assumes that a small amount of explosives is ignited by the shock heating, the reaction rate is controlled both by pressure and surface area.

\[ \dot{\lambda} = \alpha (1 - \lambda)^3 (\rho \rho_0^{\gamma - 1} - 1 - a)^\gamma + G_1 (1 - \lambda)^\gamma \lambda^\gamma P^\gamma + G_2 (1 - \lambda)^\gamma \lambda^\gamma P^\gamma \]  

where the first item indicates the hot point form and the ignition of the heating zone; the second item represents the slow growth inward or outward of the hot point; the third item expresses the rapid completion of the reaction where the \( \rho \) is the density of explosive under specific pressure.

2.1.4. MAT-PLASTIC-KINEMATIC model
This model is suited to model isotropic and kinematic hardening plasticity with the option of including rate effects into consideration. It is a cost effective model and available to shell elements. Strain rate is accounted for using the Cowper and Symonds model which scales the yield stress with the factor:

\[ 1 + \left( \dot{\varepsilon} C^{-1} \right)^{\gamma / \rho} \]

where \( \dot{\varepsilon} \) is the strain rate.

The *MAT_003 model itself has a failure criterion which is better than *MAT-JOHNSON-COOK for shell elements.

2.1.5. EOS-LINEAR-POLYNOMIAL equation state
The linear polynomial equation of state is linear in internal energy. The pressure is given by:

\[ P = C_0 + C_1 \mu + C_2 \mu^2 + C_3 \mu^3 + (C_4 + C_6 \mu + C_6 \mu^2) E \]

where \( \mu = \rho \rho_0^{\gamma - 1} - 1 \), and \( \rho \rho_0^{\gamma - 1} \) is the ratio of current density to initial density. Equation (7) and (8) have the same meaning because \( C_0 \sim C_6 \) can be expressed as related forms of the specific heat ratio:

\[ P = (\gamma - 1)E \rho \rho_0^{\gamma - 1} \]

the units of \( E \) are the units of pressure.

3. Numerical Models

3.1.1. Wing structure model
LS-DYNA software is used to establish the numerical models which are impacted by two different kinds of projectiles. The finite element model of wing structure consists of three parts: the wing cover, the front and back girder and ten ribs. All of the three parts are modelled with 163 shell elements, for all the contacts between the parts the *CONTACT-ERODING-SURFACE-TO-SURFACE contact algorithm of LS-DYNA is used without friction.

The size of wing bounding box is 1220mm \( \times \) 800mm \( \times \) 45mm, the structure thickness is equivalent to aluminium alloy due to their rigidity. Table 1 indicates the parameters of LY-12cz\cite{9}:

| \( E \) (GPa) | \( \rho \) (kg/mm\(^3\)) | \( \mu \) | \( \sigma_i \) (MPa) | \( E_i \) (MPa) | \( h \) | \( \epsilon_f \) |
|-----------|----------------|-----|--------|---------|-----|--------|
| 72        | 2.7800E-6      | 0.79| 0.51   | 0.26    | 0.014| 1.03   |

3.1.2. Damage Mechanism
The active damage mechanism is a cylindrical projectile that contains both shell and the insert explosive, while the common projectiles are steel projectiles explosion which have the same shape and
dimensions with active damage mechanism. Solid 164 element type is used in both numerical models, figure 1 shows the impact finite element model (the active damage mechanism and the cover of the wing are shown as a 1/2 model in order to express more clearly).

(a) Common damage mechanism model

(b) Active damage mechanism model

**Figure 1.** The impact finite element model of wing structure

- **Common Damage Mechanism**
  The Lagrange grid algorithm and solid 164 element type with *MAT-JOHNSON-COOK* mat keyword are used for common damage mechanism, the bounding box size is $26 \text{mm} \times 26 \text{mm} \times 39 \text{mm}$ and the velocity is 1300 m/s. The material parameters of the common damage mechanism are shown in table 2:

| Parameter | Value |
|-----------|-------|
| $\rho\,(\text{gm}^{-3})$ | 7.8500E-6 |
| $G\,(\text{GPa})$ | 78 |
| $A$ | 0.79 |
| $B$ | 0.51 |
| $n$ | 0.26 |
| $C$ | 0.014 |
| $m$ | 1.03 |
| $T_m\,(\text{K})$ | 1520 |
| $\gamma_0$ | 2.17 |
| $\alpha$ | 0.46 |

- **Active Damage Mechanism**
  Large mesh deformation will happen during the explosion process for which the element type is chosen as solid 164 with ALE options. The thickness of the shell is 3mm, while the explosive size is $20 \text{mm} \times 20 \text{mm} \times 26 \text{mm}$ which is filled in the cavity. The material and equation of state models of projectiles shell are the same as wing structure. Comp B \(^{[11]}\) is selected as the internal explosive due to its efficient killing effect. As mentioned in section 2, the material model of the explosive is *ELASTIC-PLASTIC-HYDRO* and the equation of state is *IGNITION-GROWTH-OF-REACTION-IN-HE*. The Explosion and the shell both use automatic surface to surface contact (ASS2D) while the projectile and wing structure uses eroding surface to surface contact (ESS). The properties of the parameters of explosive are presented in table 3.

| Parameter | Value |
|-----------|-------|
| $\rho\,(\text{g/m}^3)$ | 1.6300E-6 |
| $G\,(\text{GPa})$ | 3.54 |
| $\sigma_y\,(\text{GPa})$ | 0.2 |
| $w$ | 0.912 |
| $F_{\text{igmax}}$ | 0.3 |
| $a_p\,(\text{GPa})$ | 557.48 |
| $b_p\,(\text{GPa})$ | 7.83 |
| $r_{1p}$ | 4.5 |
| $r_{2p}$ | 1.2 |
| $b$ | 0.222 |
| $wcvp$ | 0.34 |
| $C_v$ | 2.48E-3 |
| $x$ | 4 |
| $a$ | 0.01 |
4. The calculation of structural node load based on MPCCI tools

MPCCI tools can realize the coupling problem between multiple disciplines by proving a single subject simulation program \cite{12}. The data can be exchanged between two or more FEM software by dividing the calculation into a number of step length, simplex data is transformed during each step and exchanged between two steps. The way uses in this paper is that the pressure which imported into MPCCI is picked up ANSYS CFD™ software by calculating the flow field outside of the wing cover, while the force on structural node is the output.

The finite element sizes of aerodynamic grid should be small enough due to the limiting calculation precision demand. It is complicated and unnecessary to use the large number of load for structural loading assessment, therefore, the pneumatic load is transferred to minor structural node for ensuring the reaction of real pneumatic load based on the simplified calculation. In this paper, the pneumatic node load is obtained at 0.83 Maher and 3.06° angle of attack with ANSYS CFD™ software, then it is transferred to structural node load by MPCCI tools. The structural node can well reacting the real pneumatic load of the wing structure. The forces of structural node and aerodynamic node are compared in figure 2.

![Figure 2. Force comparison of structural node and aerodynamic node](image)

Forces on the 72 aerodynamic nodes and 11 structural nodes distributed along the midline and the leading edge of the wing are compared separately (Node number from the wing root to tip starts from 1). Figure 3 shows the aerodynamic node force on the leading edge and the midline. Aerodynamic force decreases smoothly from root to tip. The one loads on the upper wing surface is more than on the lower surface, and on the leading edge is higher than on the midline.
The structural node force on the leading edge and the midline is shown in figure 4. Since there are far less structural nodes than aerodynamic nodes, more force contributes to each structural node than aerodynamic one. Figure 4 shows that the trend of transformed structural force agrees to aerodynamic characteristics.

5. The comparison of penetrating size and stress concentration around the damage holes
The structural node load that obtained in section 4 is loaded on the corresponding node of wing cover by the keyword *LOAD-NODE-POINT. Section 2 describes a model that the wing structure is impacted by two rows of ten projectiles at the intersection of the girders and ribs, the ten projectiles are numbered from 1 to 10 based on the position (from the root to tip, from the leading edge to the trailing edge). The penetrating holes are numbered from 1 to 20 according to the same rules as the
Projectiles which are from 1 to 10 on the bottom aerofoil while from 11 to 20 on the top aerofoil (assuming the aircraft is impacted from the bottom aerofoil).

The penetrating sizes result from no. 1 to 10 are counted at 0.3ms. Figure 5 shows the sizes of the penetrating holes under the two kinds of damage mechanism and the stress concentration around the damage holes are compared in figure 6. The abscissa is the broken holes number corresponded with the projectile.

Figure 5. The comparison of penetrating size

Figure 6. The comparison of penetrating size stress concentration.
6. Conclusions
The penetrating sizes and the stress concentration around the damage holes of metal wing structure are
recorded in order to analyse the response under the common damage mechanism and active damage
mechanism condition. In both of the numerical simulations, the aerodynamic load is well transformed
into structural load by MPCCI tools. And there is no significant differences of penetrating holes size
as well as stress concentration between the loading condition and unloading condition, while the type
of damage mechanism has a major influence on these two parameters. The damage size of wing
structure under active damage mechanism is about 15% more than common damage mechanism and
the stress concentration around the holes is almost twice of the latter. The structural damage efficiency
of active damage mechanism is significantly better than common damage mechanism.

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