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Analytical research on impacting load of aircraft crashing upon moveable concrete target

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Abstract: The impact load of an aircraft impact upon moveable concrete target was analyzed in this paper by both theoretical and numerical methods. The aircraft was simplified as a one dimensional pole and stress-wave theory was used to deduce the new formula. Furthermore, aiming to compare with previous experimental data, a numerical calculation based on the new formula had been carried out which showed good agreement with the experimental data. The approach, a new formula with particular numerical method, can predict not only the impact load but also the deviation between moveable and static concrete target.

1. Introduction

As an important barrier to ensure the safety of nuclear reactors, concrete containment, once destroyed, the consequences will be extremely serious. Since the incident of 9/11, researchers have intensified their research on the related problems of aircraft accidental impacts on nuclear power plant containment.

As the core of this issue, impact load formula proposed by Riera [1] has been used widely in this field. The core assumption of this formula is that the increase of the damaged mass is equal to the product of the flight speed and line r density of the aircraft. In 1976, considering the elastoplastic characteristic, Drittler et al. [2] modified the original Riera formula. Furthermore Hornyik et al. [3] claimed that the inertial force was overestimated as the target was considered as rigid so that a correction factor was introduced to reduce the inertial force. Riera [4] summarized the conclusions of other researchers and then additionally proposed an approach concerning oblique impact of aircraft.

Generally, in the experiment, the concrete target is set as moveable target whose acceleration can be used to calculate impact load. Experimentally, Sugano et al. [5-7] carried out the Japanese-American joint full-scale aircraft collision experiment, the only one with available experimental data all over the world up to now. In this experimental study, a lot of experimental data are obtained, including the
accelerations of the target at different positions, the velocity-time curves of aircraft components such as the engine, the fuselage and the tail, and the impact force acting on the target was calculated by using the acceleration data of the concrete target. However, there is no such theoretical wave method to estimate the deviation of impact load between static and moveable target while the impact process is absolutely wave process. As the most widely used formula, Riera formula, the core assumption of which is questionable from the point view of stress-wave theory. Therefore, present study will focus on the description of the impact load characteristic for the impact process of an aircraft upon a moveable concrete target, based on the stress wave theory, by which some novel features and physical mechanism about the impact process will be uncovered.

This paper is divided into four major sections as follows. Following this brief introduction in Section One, theoretical analysis is displayed in Section Two, in which a new formula is proposed. In Section Three, the numerical results for the impact load calculated by new impact load formula are presented and compared with both the numerical results calculated by using the Riera equation and previous experimental data, together with some necessary discussions. Finally, some conclusions are drawn out in Section Four.

2. Stress approach for impact-load formula

In order to obtain theoretical result and ignore the effects such as geometrical dispersion, aircraft structural characteristic was simplified as one-dimensional pole which is used similarly in Riera approach. In follow discussion, the new formula based on stress-wave theory will be called as SW formula as abbreviation.

As is shown in Fig.1, when the aircraft impacts upon the target, two stress waves begin to propagate in the aircraft’s fuselage in the direction of the tail, namely, a precursor elastic wave propagating at the elastic longitudinal wave speed $c_e$ and a successor generalized plastic wave with the generalized plastic longitudinal wave speed $c_p < c_e$. Moreover, the stress states behind the precursor elastic wave and the successor generalized plastic wave are generalized yield stress of the aircraft’s fuselage $\sigma_Y$ and the instantaneous impacting stress $\sigma$. Here, by “generalized plastic” we mean that the aircraft crushing is not just a pure plastic deforming or yielding process, which includes many other failure mechanisms such as fracture and buckling.

![Wave system in the aircraft fuselage](image)

**Fig.1** Wave system in the aircraft fuselage

At the beginning of the impact, $t_0 = 0$. The aircraft impact the concrete target with a velocity of $V$. The mass of the target is $M_T$ and the friction between the target and the ground is $f$. The wave process of the impact is showed in Fig.2.
Some additional assumptions are displayed below: materials of the aircraft, once destroyed, will vanish in a very short time so that the elastic wave will not propagate into crushing region which is the area after the generalized plastic wave. This assumption base on the fact that the crushing region cannot be observed in the experiment which implies the length of it is short enough to be neglected. Furthermore, the structure of the aircraft is simplified as a one dimensional pole, as we have mentioned previous, so that the aircraft will be treated as homogeneous material. Although the yield stress of the aircraft is unclear till now, we can calculate an average value alternatively from the data of the experiment. The impact process can be dissected by dividing it into some sub processes.

According to the stress-wave theory, the conservation condition cross the left-propagate elastic wave front is:

$$\sigma_2 - \sigma_1 = \rho_X c_y (V_2 - V_1)$$

(1)

Where $\sigma_1$ and $\sigma_2$ are the stresses, $V_1$ and $V_2$ are particle velocities in the corresponding area, $\rho_X$ is the bulk density of the aircraft. The stress of the 1' area is the yield stress as the impact velocity is high enough.
\[ \sigma_{y'} = \sigma_y \]  \hspace{1cm} (2)

and hence

\[ V_{L} = V_1 + \frac{\sigma_y}{\rho_x c_y} \]  \hspace{1cm} (3)

The conservation condition cross the left-propagate plastic wave front is:

\[ \sigma_{y'} - \sigma_y = \rho_x c_p (V_{L} - V_1) \]  \hspace{1cm} (4)

Substitute Eq.(2) into Eq.(4):

\[ \sigma_{y'} = \left[ 1 - \frac{c_p}{c_y} \right] \sigma_y + \rho_x c_p (V_{L} - V_1) \]  \hspace{1cm} (5)

On the other hand, the target is accelerated under the impact stress. Thus, the motion of the target can be written out by the Newton's second law and the velocity of the target is:

\[ \sigma_{y'} = \frac{M_T}{A(c_p t)} \frac{dV_{L}}{dt} + \frac{f}{A(c_p t)} \]  \hspace{1cm} (6)

Let the two previous equations equal, then an ordinary differential equation for determining the velocity of the 1"area after the generalized plastic wave can be deduced:

\[ \frac{dV_{L}}{dt} + p(t)V_{L} = q_1(t) \]  \hspace{1cm} (7)

Assume that:

\[ p(t) = -\frac{\rho_x c_p A(c_p t)}{M_T}, \quad q_1(t) = \frac{A(c_p t)}{M_T} \left[ \left( 1 - \frac{c_p}{c_y} \right) \sigma_y - \rho_x c_p V_1 - \frac{f}{A(c_p t)} \right] \]  \hspace{1cm} (8)

Considering the initial condition:

\[ V_{L} \bigg|_{V_{L} = 0} = v_0 = 0 \]  \hspace{1cm} (9)

Where, the target velocity is \( v_0 \) at initial time \( t_0 = 0 \). The general solution of the Eq.(7) can be written:

\[ V_{L} = e^{\int_{t_0}^t p(t)dt} \left( C + \int_{t_0}^t q_1(s) e^{\int_{t_0}^s p(t')dt'} dt' \right) \]  \hspace{1cm} (10)

Then, the initial condition Eq.(9) is substituted into the upper formula to determine the undetermined constant in the general solution:
\[ C = v_0 = 0 \] (11)

Thus, the solution of the ordinary differential Eq.(7) under the initial condition Eq.(11) can be written with generality:

\[ V_{1^*} = e^{-\int_{t_0}^{t_1} p^{(1)}(s) ds} \left( v_0 + \int_{t_0}^{t_1} q_1(s) e^{\int_{t_0}^{s} p^{(1)}(r) dr} ds \right), \quad (t_0 < t < t_1) \] (12)

After \( V_{1^*} \) is determined, \( \sigma_{1^*} \) may be determined by Eq.(5). The situation in area 2 will be:

\[ \sigma_2 = 0, \quad V_2 = V_{1^*} + \frac{2\sigma_y}{\rho_s c_e} \] (13)

At this point, all the status during \( t_0 - t_1 \) period have been identified. In addition, Eq.(13) provides the initial conditions for determining the next period \( (t_1 - t_2) \). Furthermore the velocity of the target at the beginning of the period from \( t_1 \) to \( t_2 \) can be calculated:

\[ v_2 = e^{-\int_{t_1}^{t_2} p^{(1)}(s) ds} \left( v_0 + \int_{t_1}^{t_2} q_1(s) e^{\int_{t_1}^{s} p^{(1)}(r) dr} ds \right) \] (14)

The method used to analysis the next period is just same to the previous one. Referring to the above equations, it is easy to write the SW impact load recurrence equation:
It is not difficult to achieve the acceleration of target in the process of aircraft impact from Eq.(6):

\[
a_a^\tau = \frac{dV_a^\tau}{dt} = \frac{A(c_p t)}{M_T} \left[ \sigma_a^\tau - \frac{f}{A(c_p t)} \right] \quad (t_{n-1} < t < t_n)
\]

The formula shows that the acceleration of target is piecewise continuous function in the SW impact load model. This is also the inevitable result of decomposing the process into a series of sub impact processes.

The velocity of the target should be considered when calculating the impact stress due to the moveable target, so that the velocity difference between the front and the back of the generalized plastic wave front in the moving target will be reduced. This may lead to a change in the generalized plastic wave velocity, thereby affecting the length of the damaged zone, etc. On the other hand, the impact load will be smaller than the impact of the aircraft on the stationary target. When the airplane hits the moveable target, its velocity and acceleration are determined by the impact load, the motion friction resistance and the mass of target. Generally, in the experimental study, if the mass of the target is large enough, the data of acceleration sensor would not be precise. On the other hand, the impact load would be effected if the concrete target is too light. In the actual situation, the nuclear
containment considered not destroyed, otherwise, it is meaningless to analyze the impact load of the aircraft impact. Therefore, in order to be closer to the actual situation, the mass of concrete targets should not be too small. Therefore, how to select the appropriate mass of concrete target is an important problem in the aircraft impact experiment, and the analysis of these targets provides a theoretical basis for solving this problem.

3. Numerical results and discussions

Moveable target experiment is an effective method to measure the impact load of aircraft impact upon nuclear containment. Therefore, the impact load formula is considered to estimate the impact force in both experimental and actual conditions. Furthermore, the difference of the impact load between the two conditions should also be estimable. In this part, considering the linear density of the aircraft, the impact load and some other parameters will be discussed via numerical ways.

The tolerance of the impact load between moveable and stationary is showed by percentage in Fig.3 which is calculated using Eq. (15):

![Fig.3 Impact load tolerance between moveable and stationary target over different times of the target mass](image)

As showed in Fig.3, the impact load tolerance between moveable and stationary target increases over time. Because the velocity of the moveable target is 0 at the beginning of the impact. Apparently, the larger mass of the moveable target (the ratio of the target mass to the aircraft mass) the more precise data could be achieved by experiment, however the cost and the accuracy should be considered simultaneously. The impact load of an aircraft impact upon a moveable target which has a mass that is 5 times of the aircraft is showed below:
The difference is conspicuous if the mass of the moveable target is light enough. However, in Japanese-American joint full-scale aircraft collision experiment, the mass of the target is 25 times of the aircraft. In order to test the new equation, the velocity of the target over time is calculated and also compared with the experimental data as follow:

The comparison between the experimental data and numerical result shows good agreement so that the new impact formula can be used to estimate the impact force and also some other parameters.
4. Conclusions

The SW formula is based on stress-wave theory which shows more details than the original Riera formula. Furthermore, the SW formula can also predict the tolerance between the experimental and actual impact force which is a robust tool for researchers to decide the mass of the moveable concrete target before the experiment.

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