Nuclear Engineering and Design 294 (2015) 86–92

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Revisiting Riera's model about malevolent aircraft impinging against a rigid target

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HIGHLIGHTS

- The Riera's model is revisited.
- The impulse on rigid target is about equal to the initial momentum of aircraft.
- Ratio of initial kinetic energy to the limit plastic strain energy is obtained.
- Riera's model is improved by considering the reflection of debris.
- Modification coefficient of the dynamic force is proposed.

ARTICLE INFO

Article history:
Received 27 March 2015
Received in revised form 30 July 2015
Accepted 15 August 2015
Available online 6 October 2015

I. Reactor protection

ABSTRACT

This paper revisited the Riera's model which is known as an important theoretical model of describing a malevolent aircraft impact on a rigid target for which the engineering background is against the crashworthiness design of the protecting shell in nuclear power plant subjected to terrorist attack. The relationship among the initial momentum of the aircraft, the total impulse exerted on the rigid target, the impulse of the crushing pressure, and the impulse of the dynamic pressure were studied. It was proved that the impulse exerted on the rigid target during the impact period is approximately equal to the initial momentum of aircraft. The expression of the ratio of the initial kinetic energy of the aircraft to the limit plastic strain energy that results in the crash of the aircraft was obtained. In addition, this study demonstrated that the reflection of a large number of debris increases the impulse exerted on the target and therefore the Riera's model needs to be improved by considering this effect and the modification coefficient of the dynamic force was proposed.

1. Introduction

The crashworthiness design of the protecting shell in Nuclear Power Plant (NPP) subjected to terrorist attack is of strategic significance because the damage of the structure may lead to the leakage of nuclear radiation and bring horrific consequence (Abbas et al., 1996).

To assess the effects of aircraft impacts on NPPs, the aircraft impact force has to be estimated for expected loadings. Riera (1968) was the first to study this problem who presented a theoretical model to investigate the impact force properties by considering normal impact upon a rigid target and the time history of the aircraft impact force was obtained. Then, many studies have been conducted using Riera's method about the malevolent impact of a high-speed military aircraft or large commercial aircraft (Petrangeli, 2010; Frano and Forasassi, 2011; Iqbal et al., 2012). Wolf et al. (1978) showed that the reaction-time curve for a large commercial aircraft as obtained by Riera is practically indistinguishable from that obtained by modeling the aircraft with lumped masses interconnected by elasto–plastic springs. Kinsella and Jowett (1989) presented a rather crude linear scaling procedure to group a range of military combat aircraft and determined the reaction response for normal impact upon a rigid target. Hornyik (1977) attempted to improve Riera's formulation by considering energy balance as well by assuming rigid perfectly plastic behaviour of the missile material.

Except for the well-known Riera's model for aircraft impact time history data, the finite element analysis (FEA) method using

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http://dx.doi.org/10.1016/j.nucengdes.2015.08.019
0029-5493/

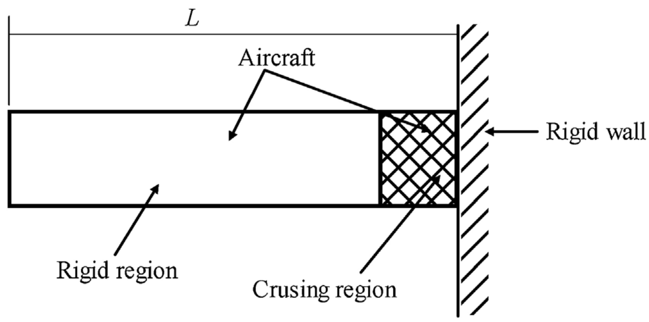

Fig. 1. Illustration of aircraft striking rigid target.

high-quality FE models of aircraft (Arros and Doumbalski, 2007; Jeon et al., 2012) has also been used to study the aircraft impact problems. The latter method is usually called the missile–target interaction analysis method. Tennant et al. (2014) developed a Rapid Assessment Aircraft Impact Tool to provide rapid assessment of damage to civilian structures caused by aircraft impact. Analysis of an aircraft crash upon an outer containment of a NPP was presented by Abbas et al. (1995, 1996). The effect of target yielding was considered simultaneously by calculating the reaction time in a time marching scheme. The response for different cracking strains and different locations of aircraft strike for different aircraft was studied. Arros and Doumbalski (2007) presented numerical analysis of aircraft impact to NPP structures utilizing a simplified model of a "fictitious nuclear building". Lee et al. (2013) presented the numerical results of nonlinear dynamic analyses of a concrete containment building under the impact of a large commercial B747 airliner, and a rigid wall impact test was performed using commercial nonlinear finite element codes.

Most of the existing literatures mainly studied the time history of the aircraft impact force and few works was related to the impulse and energy of the aircraft and NPP. Among them, the ratio between kinetic energy and plastic impinging force of the missile was studied first by Riera (1982). Similar analysis was demonstrated by Rambach et al. (2005). In addition, the published theoretical models didn't consider the reflection of aircraft debris on the surface of the target. Actually, the reflection of a large number of debris increases the impulse exerted on the target, the reason being that as a large number of particles strike on a free surface with initial velocity, some particles diminish their velocities to zero and deflect in the opposite direction. According to the principle of linear impulse and momentum, the impulse exerted on the free surface is larger than the initial momentum of the particles. Based on this, the Riera's model needs to be improved by considering the reflection of debris and a modified Reira's model will be presented in this paper. On the other hand, the ratio of the initial kinetic energy of the aircraft to the limit plastic strain energy is derived and it is verified that the initial kinetic energy of the aircraft is much larger than the limit plastic strain energy during the impact period. Finally, the accuracy of the theoretical model is verified.

2. Analysis of momentum and impulse during aircraft impact

2.1. Basic governing equations

As an aircraft strikes a target, a part of it close to the target gets crushed and the remaining portion of it undergoes elastic deformation, which, from the point of view of deformation, may be regarded as rigid with not much error (Riera, 1968, 1980). So, consider an aircraft to consist of a thin crushing zone and a rigid zone as shown in Fig. 1.

According to Riera's model, at the moment the aircraft is crushed, the impact force, R_c, exerted on the rigid target is

$$R_c = P_c + \rho v^2 \tag{1}$$

where P_c is the load necessary to crush or buckle the aircraft, ρ and v are the mass per unit length and the instantaneous velocity of aircraft at the instant of crushing.

According to the principle of linear impulse and momentum, one can get

$$P_c = -\rho L \frac{dv}{dt} \tag{2}$$

where L is the instantaneous length of the aircraft.

On the other hand, based on the continuous equation, the relationship between the instantaneous velocity and instantaneous length is

$$\frac{dL}{dt} = -v \tag{3}$$

Assume that the distributions of ρ and P_c along the length of the aircraft are described by the following functions:

$$\begin{aligned} \rho &= \rho_0 f_1(L) \\ P_c &= P_0 f_2(L) \end{aligned} \tag{4}$$

It can be obtained from Eqs. (2)–(4) that

$$v^2 = v_0^2 + \frac{2P_0}{\rho_0}\Phi(L) \tag{5}$$

where

$$\Phi(L) = \int_{L_0}^{L} \frac{f_2(x)}{f_1(x)x} dx \tag{6}$$

and L_0 and v_0 are the initial length and initial velocity of the aircraft.

Letting $v = 0$ in Eq. (5) yields

$$v_0^2 = \frac{2P_0}{\rho_0}\Psi_e \tag{7}$$

where

$$\Psi_e = \int_{L_e}^{L_0} \frac{f_2(L)}{f_1(L)L} dL \tag{8}$$

and L_e is the residue length of the aircraft.

2.2. Relationship between the impulse of the forces exerted on the rigid target and the initial momentum of the aircraft

Substitution of Eq. (7) into Eq. (5) yields

$$v^2 = v_0^2\left[1 + \frac{1}{\Psi_e}\Phi(L)\right] \tag{9}$$

It can be obtained from Eqs. (3) and (9) that

$$dt = \frac{-dL}{v_0\sqrt{1 + \left(1/\Psi_e\right)\Phi(L)}} \tag{10}$$

Substitute Eq. (4) into Eq. (1), and combine with Eq. (9), one can get

$$R_c = P_0 f_2(L) + \rho_0 f_1(L) v_0^2\left[1 + \frac{1}{\Psi_e}\Phi(L)\right] \tag{11}$$