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Numerical simulations of nuclear power plant containment subjected to aircraft impact

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HIGHLIGHTS

- Fine FE models of Ling Ao NPP prestressed containment and A320 aircraft are established and calibrated.
- Dynamic responses of NPP containment are simulated and compared by the coupled and decoupled methods.
- Parametric study (impact position, velocity, etc.) on the deflection-time history of containment is performed.
- An explicit formula is proposed to predict the maximum deflection of containment against aircraft collision.

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ABSTRACT

Since the September 11 attacks, the protective performance of the nuclear power plant (NPP) containment against the impact of large commercial aircraft has been drawing much attention in the field of nuclear security. This paper addresses the numerical simulations of NPP containment subjected to aircraft impact. Firstly, the fine FE models of the Chinese Ling Ao NPP prestressed containment and A320 aircraft are established, and calibrated by the prototype impact test of GE-J79 engine and the modified Riera function, respectively. Then, based on the verified FE models, the entire impact process of the aircraft collision with the containment is reproduced by the missile-target interaction method, which is preferable by comparing with the loading-time history method in analyzing the dynamic responses of the containment. Furthermore, the parametric study is performed to investigate the influences of impact condition (position, angle and velocity) and structural configuration (wall thickness, reinforcement ratio and prestressing force) on the deflection-time history of the NPP containment in the impact central zone. Finally, an explicit formula for predicting the maximum impact deflection of the containment against the aircraft collision is proposed, which is helpful for the engineers in designing the NPP containment.

1. Introduction

The nuclear power plant (NPP) containment is the outermost and last safety barrier of the nuclear fuel reactor, whose protective performance is very critical to prevent the leakage of inner fission fuel. With the increasingly rampant of the terrorist attacks as well as the rapidly growing number of the in-service aircrafts, the NPP containment is confronted with more and more deliberate and accidental aircraft impact threats. Before 2001, the NPP containment was not specifically designed to resist the collision of large commercial aircraft. However, since the September 11 attacks, NPP containment subjected to large commercial aircraft impact has attracted much attention in the field of nuclear safety. In 2009, the USA Nuclear Regulatory Commission (NRC, 2009) required that new NPP containment to be built must take into consideration of the large commercial aircraft impact (Jiang and Chorzepa, 2014).

The determination of the aircraft impact force is critical to assess the damage of the containment. Riera (1968) firstly developed a one-dimensional rigid-perfectly plastic model to calculate the normal impact force of aircraft hitting on a rigid flat target, which is recognized as the Riera function and widely used thereafter. Dritter and Gruner (1976) further put forward a difference method to calculate the impact force by considering the elastic-plastic material properties of the aircraft. Afterwards, Wolf et al. (1978) proposed a lumped mass-spring model and the calculated results fit well with that of the Riera function. During the actual impact process, the flying debris broken away from the aircraft will lead to the losses of energy and mass, which may weaken the

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impact force, and then some modifications to the Riera function were performed (Hornyik, 1977; Bahar and Rice, 1978; Kar, 1979). However, the accurate modification value was not obtained until that a prototype F-4 fighter impact test was conducted by Sugano et al. (1993a), which confirmed that the Riera function with a reduction coefficient 0.9 for the inertial item was a practical way to calculate the aircraft impact force.

Due to the complex experimental techniques and great expenditure, nearly no open prototype test of the commercial aircraft impacting on the actual NPP containment has been conducted. Meanwhile, the rapid development of the FE program motivates the use of numerical simulation to study this issue. Generally, two simulation methods are commonly utilized: the loading-time history method (decoupled simulation) (Abbas et al., 1996; Petrangeli, 2010; Frano and Forasassi, 2011; Iqbal et al., 2013; Sadique et al., 2013) and the missile-target interaction method (coupled simulation) (Itoh et al., 2005; Siefert and Henkel, 2014; Lee et al., 2013, 2014). The decoupled simulation does not need the aircraft FE model and apply the impact force on the structure directly, while the loading-time history should be derived in advance. The coupled simulation could reproduce the entire impact process more realistically and consider more impact conditions, while the verified fine FE models are necessary. Some related studies (Itoh et al., 2005; Siefert and Henkel, 2014; Lu et al., 2015) pointed out that, in order to improve the accuracy of the simulation analysis, the fine FE models which could reflect the actual structures as much as possible are rather critical. However, in most of the existing literatures, some significant details of the FE models were not considered or established, such as the prestressed tendon and the corresponding conduit of the NPP containment, as well as the aviation fuel and interior structure of the aircraft engine. Besides, the validities of the FE models are almost not verified reasonably.

In this paper, the fine FE models of the Chinese Ling Ao NPP prestressed containment and the A320 commercial aircraft are firstly established, which are calibrated by the prototype impact test of GE-J79 engine (Sugano et al., 1993b,c) and the modified Riera function (Sugano et al., 1993a), respectively. Then, the missile-target interaction method and loading-time history method are utilized to study the dynamic responses of the containment under aircraft collision, respectively. The simulated results, e.g., the concrete damage, effective plastic strains of steel liner and rebar, axial force of prestressed tendon and impact deflection, are compared and discussed. Finally, for the NPP containment designers, based on a series of parametric studies, an easy-to-use formula for predicting the maximum impact deflection of the containment against the aircraft collision is proposed.

2. FE models

In this section, by using the modelling software HyperMesh (Altair HyperWorks, 2010), the fine FE models of the Ling Ao NPP prestressed containment and the A320 aircraft are established. Then, the above FE models are incorporated into the FE program LS-DYNA (Hallquist et al., 2013) and the numerical simulation is performed.

2.1. Ling Ao NPP containment

The prestressed concrete containment is widely adopted in the nuclear power plants, such as the Ling Ao NPP containment in China, which is analyzed at present. The containment structure mainly consists of the concrete, the steel liner, and the components which are embedded in the concrete, such as the rebars, the prestressed tendons and its outer conduits. The tendons can move in the conduits and be retighten when they relax. The prestressing forces of tendons along the circumferential and longitudinal directions are 4e6 N and 8e6 N, respectively. In most of the existing related literatures, the conduits as well as the slip of the tendons in the conduits were neglected.

Fig. 1 shows the FE model of Ling Ao NPP containment. As shown in Fig. 1(a), considering the symmetry, only the 1/2 model is established to save the computing time. Fig. 1(b) illustrates the arrangement details of the containment and the element type for each component, and totally about 1.5 million elements are created. The detailed dimensions of both rebars and prestressed tendons are given in Fig. 2.

The bottom of the containment FE model is fixed and the steel liner is connected to the concrete by joint nodes. The keyword CON TACT_AUTOMATIC_NODES_TO_SURFACE is adopted to ensure the contact between the prestressed tendons and the outer conduits, and the prestressed tendons do not interact with the concrete directly. The interaction between the conduits and the concrete is realized by the keyword CONSTRAINED_LARGRANGE_IN_SOLID, which is also used for the rebars and the concrete. Besides, the keyword CONTROL_DYNAMIC_RELAXATION is utilized to exert the prestressing forces of the tendons.

The material constitutive model of MAT_CSCM_CONCRETE (MAT#159) is adopted to model the concrete, which is simple to input the material parameters, as listed in Table 1. The steel liner, rebar, prestressed tendon and its outer conduit are modelled by the MAT_PLASTIC_KINEMATIC (MAT#3) and the parameters are listed in Table 2.

2.2. A320 aircraft

Airbus A320 is the most widely used in-service commercial aircraft all over the world. Its maximum takeoff weight, length of fuselage and wingspan are about 78t, 38 m and 34 m, respectively. Due to the great complexity and confidentiality of the actual A320 aircraft, following our previous work (Zhang et al., 2015), the primary components of aircraft are considered as follows: (i) the main load-carrying beams, which build the frames of the fuselage, the wings, the floor and the landing gears; (ii) the secondary structures, such as the ribs, connecting members, outer skin and floor surface; (iii) the power system, such as the aviation fuel, tanks and engines; (iv) additional payloads, such as the passengers, seats, electronic equipment, luggage, etc.

The FE models of A320 aircraft as well as the main components, e.g., fuselage frame, engine, fuel and tanks, are shown in Figs. 3 and 4. The models consist of beam elements for the beam components, shell elements for the skin, tanks, engines and floor surface, SPH (Smoothed Particle Hydrodynamics) elements for the aviation fuel,

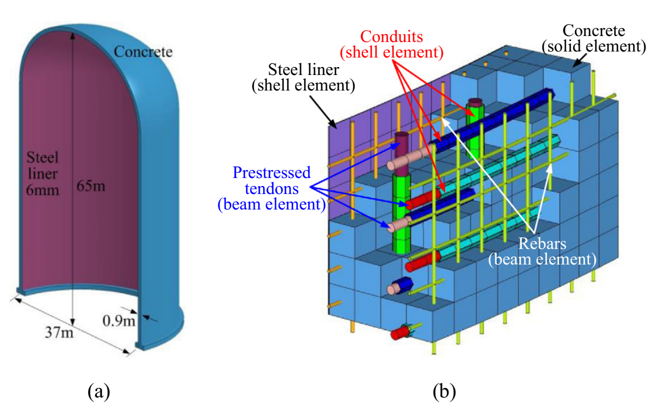

Fig. 1. Ling Ao NPP containment model (a) geometry (b) detailed arrangement.