Nuclear Engineering and Design 276 (2014) 228–240

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Effects of reinforcement ratio and arrangement on the structural behavior of a nuclear building under aircraft impact

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HIGHLIGHTS

- Numerical analysis of RC nuclear building model under aircraft impact was conducted.
- The analysis result shows similar behavior as compared to the Riera function.
- The effects of reinforcement ratio and arrangement were enumerated.
- The appropriate number of layer of longitudinal rebar was recommended.

ARTICLE INFO

Article history:
Received 3 November 2013
Received in revised form 7 April 2014
Accepted 9 April 2014

ABSTRACT

This study presents the effectiveness of the rebar ratio and the arrangement of reinforced concrete (RC) structures on the structural behavior of nuclear buildings under aircraft impact using a finite element (FE) approach. A simplified model of a fictitious nuclear building using RC structures was fully modeled. The aircraft model of a Boeing 767-400 was used for impact simulation and was developed and verified with a conventional impact force–time history curve. The IRIS Punching test was used to validate the damage prediction capabilities of the RC wall under impact loading. With regard to the different rebar ratios and rebar arrangements of a nuclear RC building, the structural behavior of a building under aircraft impact was investigated. The structural behavior investigated included plastic deformation, displacement, energy dissipation, perforation/penetration depth and scabbing area. The results showed that the rebar ratio has a significant effect on withstanding aircraft impact and reducing local damage. With four layers of rebar, the RC wall absorbed and dissipated the impact energy more than once with only two layers of rebar for the same rebar ratio.

1. Introduction

An aircraft crashing into a structure is considered to be extremely hazardous and could almost certainly cause extensive damage to a building. The evaluation of airplanes crashing into a fictitious auxiliary nuclear building has become necessary since the U.S. Nuclear Regulatory Commission (U.S. NRC) has determined that the impact of a large, commercial aircraft is a beyond-design-basis event.

To provide a calculation method for the equivalent impact force, Riera (1968) proposed a formula to evaluate the reaction–time relationship in the case of an accidental impact of a large commercial aircraft against a rigid wall. According to Riera's proposal, the total reaction $P(t)$ is the function of crushing force $P_c(x)$, mass per unit length $\mu(x)$, and velocity of uncrushed portion: $P(t)=P_c(x)+\mu(x)v^2(t)$. Subsequently, Wolf et al. (1978) checked the validity of Riera's approach on calculating the impact force of an aircraft crash using Boeing 707 impacting into a rigid target. Bahar (1978) and Kar (1979) modified Riera's equation by introducing the coefficient α into the second term of Riera's equation. Based on the experimental results of the full-scale aircraft impact test of an F-4 Phantom on a massive target, Sugano et al. (1993a) determined the values of α as from 0.7 to 1.0.

Another work of Sugano et al. (1993b) was a series of engine model impact tests on a reinforced concrete panel. Riedel et al. (2010) also conducted a series of scaled aircraft engine impact tests on reinforced UHPC panels. Local damage of reinforced concrete and reinforced UHPC panels was determined and classified into four to five major modes.

The study of Zerna et al. (1976) dealt with the optimization of reinforcements for resisting impact forces resulting from an aircraft crash. Dundulis et al. (2007) studied nonlinear behavior of

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http://dx.doi.org/10.1016/j.nucengdes.2014.04.013
0029-5493/

Table 1
Material properties of the nuclear building and aircraft models.

Material	Modulus of elastic E (GPa)	Poisson ratio, ν	Density, ρ (kg/m^3)	UCS (MPa)	UTS (MPa)	Failure strain (%)	Aggregate size (m)
Concrete	32.8	0.15	2190	58	4.1	–	0.008
Steel	200	0.3	7850	540	540	25.00	–
Aluminum alloy 2024-t351	73.1	0.33	2837.5	290	290	–	–

an INPP ALS building subjected to a Phantom RF-43E crash. Jin et al. (2011) developed an FE model of a large aircraft engine and evaluated the localized damage of a concrete wall. The behavior of nuclear power plant containment subjected to an aircraft crash was also carried out by Abbas et al. (1996). Arros and Doumbalski (2007) performed an analysis of a Boeing 747-400 aircraft impact on a concrete building using LS-DYNA. In Arros' works, the comparison of shock loading obtained from the Riera force history analysis with that from the missile-target interaction analysis was carried out, and sensitivity studies were also conducted. In the preliminary evaluation of aircraft impact on a nuclear containment of Frano and Forasassi (2012), the effects of different wall thicknesses and reinforced/prestressed concrete was carried out as a sensitive analysis.

Although the mentioned studies focused on a wide range of aircraft impact investigation, the evaluation of the influence of the rebar ratio and arrangement on structural behavior of an auxiliary nuclear building has still not been carried out. In this study, the effect of the rebar (horizontal rebar and vertical rebar is called "rebar") ratio and the number of rebar layers on local and global damage of the auxiliary nuclear building was investigated while the wall thickness was assumed to be constant. A three-dimensional numerical impact simulation of a Boeing 767-400 into the nuclear building was modeled using the LS-DYNA program. The fictitious auxiliary nuclear building model, adopted and modified from the work of Arros and Doumbalski (2007), was used. The numerical analysis focused on the following issues:

- Impact force–time history was verified by comparing with that of the Riera approach.
- The damage prediction capabilities of the RC wall under impact loading were validated using the IRIS Punching test.
- The structural behavior of the building with different rebar ratio was investigated.
- The analyses of RC walls with two, three, and four layers of rebar were performed respectively to investigate the influence of the rebar arrangement in regard to the punching resistance of RC walls.

The numerical results for the structural behavior, including plastic deformation, displacement, energy dissipation, perforation/penetration depth and scabbing area were discussed. An efficient design of RC wall was recommended.

2. Finite element model

2.1. General

The finite element code, LS-DYNA (version 971s R5.1.1) (Livermore Software Technology Corporation, 2007) was used for the analyses. The building, rebar and airplane were modeled separately and subsequently assembled to develop the full model using LS-PREPOST V4.0. The appropriate constraints and contacts were applied between all contact surfaces.

2.2. Nuclear building

In this study, a fictitious auxiliary nuclear building (Fig. 1), which looks those in Arros and Doumbalski (2007), was taken into account to study its local and global structural behavior. The thickness of all the concrete walls was assumed to be 1.2 m, whereas the thickness of the floor slabs was 0.72 m. All walls and slabs of the building were reinforced with horizontal and vertical rebar as shown in Fig. 1c.

The front wall of the nuclear building (see Fig. 2) was designed with three different RC wall types. The regular RC wall type, named RCW-A, has two layers of rebar as shown in Fig. 1c. The first proposed RC wall type, named RCW-B, has three layers of rebar as shown in Fig. 3a. The second proposed RC wall type, named RCW-C, has four layers of rebar as shown in Fig. 3b. The layers of rebar are equally spaced for all RC wall types. All the three RC wall types have 300 mm rebar spacing, 100 mm concrete cover, and have no shear bars. The compressive strength of the concrete building determined by cylindrical test is 58.0 MPa. The yield strength of the steel rebar is 540 MPa. The failure strain of the steel rebar is 25.0%. Table 1 lists the material properties of the concrete, rebar, and other steel parts.

Fig. 4 shows the FE modeling of the nuclear power plant building. The concrete building was modeled with a solid element. Hughes-Liu beam element (type 1) was used to model the steel rebar. A finer element mesh was employed to the front half of the building. It includes five layers along the thickness of the walls and three to five layers along the thickness of the slabs since a comparative analysis between three and six layers over the slabs showed similar results. A course element mesh was employed to the back half of the building. The total number of elements of the components of the full model is shown in Table 2.

2.3. Aircraft

The aircraft used for impact simulation is a Boeing 767-400, which is shown in Fig. 5a. This aircraft is widely used in civil flights all over the world. The main parameters of the Boeing 767-400 have been presented in Electric Power Research Institute (2002). The maximum takeoff weight for this aircraft is 200.11 tons (450,000 lb), including 90,770 l (23,980 gallons) of fuel. It has a wingspan of 51.9 m (170 ft.), an overall length of 61.3 m (201 ft.), a fuselage diameter of 5 m (16.5 ft.) and two engines weighing 4.56 tons (9,500 lb) each. The assumed speed of the aircraft is 150 m/s (350 miles per hour) as proposed by the Electric Power Research Institute (2002) since this speed has been indicated to be reasonable for the evaluation of an aircraft crash into a nuclear power plant. Aluminum alloy AL2024-T351, having a yield stress of 290 MPa, elastic modulus of 73,100 MPa and density of 2837.5 kg/m^3, is used for the airplane material. Fig. 5b shows the FE model of the airplane using the shell element.

Table 2
Total element numbers of the full model.

Components	Beam elements	Shell elements	Solid elements
Walls and slabs	–	–	377,718
Rebar	67,233	–	–
Airplane	–	17,645	–
Total	67,233	17,645	377,718