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Simulation analysis of impact tests of steel plate reinforced concrete and reinforced concrete slabs against aircraft impact and its validation with experimental results

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HIGHLIGHTS

- Simulation analysis is carried out with two constitutive concrete models.
- Winfrith model can better simulate nonlinear response of concrete than CSCM model.
- Performance of steel plate concrete is better than reinforced concrete.
- Thickness of safety related structures can be reduced by adopting steel plates.
- Analysis results, mainly concrete material models should be validated.

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ABSTRACT

The steel plate reinforced concrete and reinforced concrete structures are used in nuclear power plants for protection against impact of an aircraft. In order to compare the impact resistance performance of steel plate reinforced concrete and reinforced concrete slabs panels, simulation analysis of 1/7.5 scale model impact tests is carried out by using finite element code ANSYS/LS-DYNA. The damage modes of all finite element models, velocity time history curves of the aircraft engine and damage to aircraft model are compared with the impact test results of steel plate reinforced concrete and reinforced concrete slab panels. The results indicate that finite element simulation results correlate well with the experimental results especially for constitutive winfrith concrete model. Also, the impact resistance performance of steel plate reinforced concrete slab panels is better than reinforced concrete slab panels, particularly the rear face steel plate is very effective in preventing the perforation and scabbing of concrete than conventional reinforced concrete structures. In this way, the thickness of steel plate reinforced concrete structures can be reduced in important structures like nuclear power plants against impact of aircraft. It also demonstrates the methodology to validate the analysis procedure with experimental and analytical studies. It may be effectively employed to predict the precise response of safety related structures against aircraft impact.

1. Introduction

After 9/11 incident, the nuclear power plants (NPPs) have become significant focus of nuclear safety against impact of large commercial aircrafts. The design of NPPs must include multiple redundant systems to ensure essential nuclear safety functions, such as reactor core cooling and integrity of containment structure in all the considered conditions. These functions should be maintained particularly during the external human induced events like large aircraft impact. The latest U.S. Nuclear Regulatory Commission (NRC)'s regulations for nuclear power reactors (issued in 2009) require to perform a design specific assessment regarding impact of a large commercial aircraft on the facility. The NRC believes that it is prudent for nuclear power plant designers to take into account the potential effects of the impact of a large commercial aircraft. The NRC has determined that the impact of a large commercial aircraft is a beyond design basis event (U.S. NRC RG,

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2011). Due to insufficient experimental and analytical data for impact of large commercial aircraft, it is a challenging task to accurately predict the behavior of important structures against impact loadings.

Wang et al. (2007) presented that conducting high-speed penetration tests are costly and tedious job. In order to decrease the number of experiments required, the availability of faster and cheaper computing power is beginning to allow numerical simulation. This numerical simulation plays a vital role in predicting the complex interaction of a projectile with concrete. Numerical simulation provides a rapid and less expensive way to evaluate new design ideas. It can provide quantitative and accurate details of stress, strain, and deformation fields that would be very expensive or difficult to reproduce experimentally (Quan et al., 2003). The simulation analysis and validation with test results is useful to illustrate that finite element method (FEM) using appropriate constitute material models accurately predict the structural behavior against aircraft impact. In previous studies, several techniques for improving the impact resistance of conventional reinforced concrete structures have been proposed. These studies concluded that attaching a thin steel plate to the rear-face of a reinforced concrete (RC) panel is considered to be one of the most effective technique (Mizuno et al., 2005a). Sugano et al. (1993) carried out full scale impact tests using actual aircraft engines and reported that a thin corrugated steel liner attached to the rear-face of the concrete panel had significant effect in preventing scattering of scabbed concrete debris from the rear face of the panel.

In this paper, simulation analysis of steel plate reinforced concrete (SC) and reinforced concrete (RC) panels with different thicknesses is performed. The results are compared and validated with impact tests results and analytical studies done by Mizuno et al. (2005a,b), Tsubota et al. (1999), Morikawa et al. (1999). In their studies, impact tests results (also called experimental results) were also simulated by using discrete element method (DEM). This method idealizes concrete/steel medium as an assemblage of particles that have to satisfy equation of motion, and dynamic characteristics of whole body are expressed by the forces transferred between particles during contact (Morikawa et al., 1999). In this simulation analysis, nonlinear dynamic finite element analysis software ANSYS/LS-DYNA is used. The explicit method of solution used by LS-DYNA provides fast solutions for short time, large deformation dynamics, quasi-static problems with large deformations and multiple nonlinearities and complex contact/impact problems (Canonsburg, 2009). It provides a variety of nonlinear material models to simulate concrete and steel material behavior. Each model is developed for a specific application and requires a different set of input parameters. On the basis of extensive studies and reduced set of input parameters, two constitutive models i.e. winfrith model (*MAT_084) and CSCM concrete model (*MAT_159) are selected. For rebars, steel plates and studs, material model *MAT_PLASTIC_KINEMATIC is employed with erosion option based on plastic strain. Comparison of results is made between (i) FEM simulation analysis results of RC and SC panels with tests results, (ii) SC and RC simulation analysis results, (iii) the results obtained in FEM simulation analysis with the calculated results of discrete element method (DEM) (Mizuno et al., 2005b; Morikawa et al., 1999), and finally (iv) energy balance histories for different panel thicknesses. The comparison of analysis and tests results validated the whole methodology and increased the confidence for the full scale impact analysis of RC and SC structures of nuclear power plants against large commercial aircraft impact.

2. Experimental models for aircraft impact

Details of experimental study of 1/7.5 scale models of aircraft and different thicknesses of SC and RC slab panels are provided in references (Mizuno et al., 2005a; Tsubota et al., 1999). In case of SC panels, two types of panels were used for experiments, i.e. full SC and half SC with 60 mm, 80 mm and 120 mm thicknesses (HSC-60, FSC-60, FSC-80, HSC-80 and HSC-120). While for RC panels, experiments were carried out with thickness of 60 mm, 80 mm and 100 mm reinforced concrete slabs (RC60 RC80, RC100). In full SC panels, steel plates were used at both front and back surface of concrete while in half SC panel, rebars were used at front surface and steel plate at back surface of concrete. In impact tests, aircraft model with total weight of 247.6 N and 1.350 m length was accelerated to impact velocity of about 150 m/s and collided with RC and SC panels in free flight (Mizuno et al., 2005a; Tsubota et al., 1999).

Fig. 1 shows the gas propelled launcher facility including the major components like acceleration cart, a two-rail support track, a cart stripper, a piston acceleration tube and a piston catcher tank. When the aircraft model attached to acceleration cart reached the desired velocity, the cart was separated from the aircraft model. It was then allowed to collide with the SC panel in free flight (Mizuno et al., 2005a). The figure also illustrates the aircraft model and the SC panel set on the launcher facility. Plan view of half steel plate reinforced concrete panel (HSC-80) with reinforcement (rebar size of 6 mm diameter) and studs details on steel plate is shown in Fig. 2 as a typical example of SC panels. In the tests, HSC-80 panel was mounted on a reaction frame at their four corners by tensioned bolts (Mizuno et al., 2005a). The reinforcement details of the 80 mm thick reinforced concrete slab panel (RC80) are shown in Fig. 3 as a typical example. The steel bars of 6 mm diameter (D6) were provided at 85 mm spacing along both sides of RC80 panel. Section A–A′ indicates the thickness of RC panel and dimensions of anchor plate used along the perimeter of RC panel in impact test. Fig. 4 represents the schematic diagram of the 1/7.5 scale aircraft model used in impact tests (Mizuno et al., 2005a; Tsubota et al.,

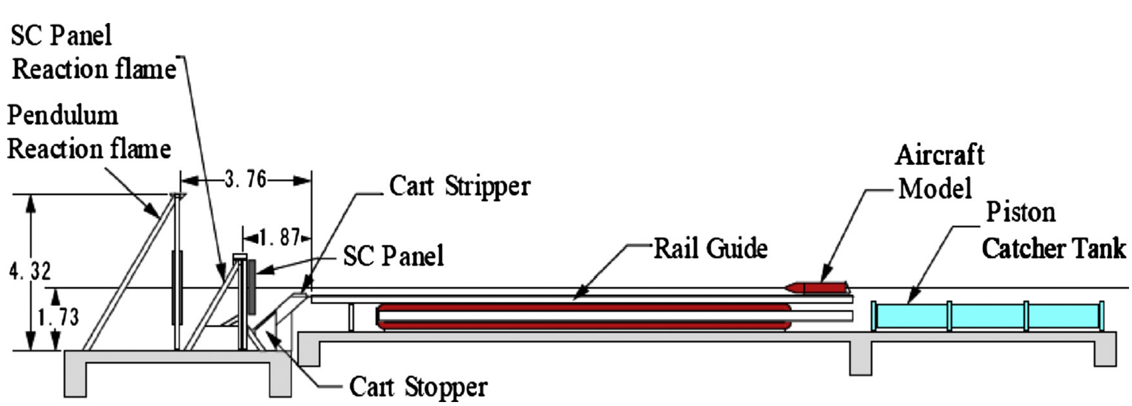

Fig. 1. Gas propelled launcher facility (Mizuno et al., 2005a).