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Nuclear containment structure subjected to commercial aircraft crash and subsequent vibrations and fire

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HIGHLIGHTS

- We analyze loading conditions including containment penetration, vibration, and fire.
- Containment vessel-soil model can predict transient and vibration responses.
- Fire resistance of containment is assessed.

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ABSTRACT

An aircraft crashing into a nuclear containment vessel may induce a series of disasters related to containment capacity, including local penetration and perforation of the containment, intensive vibrations, and fire ignited after jet fuel leakage. A procedure was presented for investigation of structural capacity of the containment of the newly developed Generation III$^+$ nuclear power plants (NPPs) in accidental scenarios. A containment vessel-soil model was developed and verified to investigate the transient response of the containment and subsequently induced vibrations on the ground surface. Ground vibrations can be used as input data to obtain the vibration of equipment inside the containment or inside buildings adjacent to the containment. Impact action was represented using a force-time history function imposed on the crash area of the containment surface. Then, a thermal analysis was conducted to predict the temperature fields following a mechanical-thermal stress analysis for fire resistance assessment. Results found the containment vessel-soil model was capable of predicting the transient and vibration responses of the structure. For the effect of impact positions on ground vibration outside the containment, impact positions in the mid-height and bottom portions of the containment induced slightly intensive ground vibration compared to impact in the upper portion of the containment. Thus, appropriate impact position should be considered when ground vibration response is a concern. Structural safety associated with fire effect was generally ensured mainly due to the low thermal inertia of concrete.

1. Introduction

Containment vessels in nuclear power plants (NPPs) are built to protect the plant, public and environment from nuclear radiation in an unforeseen event. Traditionally, an aircraft crash is considered as a potential hazard and must be included in design procedure. In particular, since the September 11, 2001 attacks on the World Trade Center in New York, NY, USA, the impact of a large commercial aircraft on containment structures has been regulated as a beyond-design-basis event (BDBE) by the U.S. Nuclear Regulatory Commission (NRC, 2009). An involved safety assessment has been required for new NPPs through realistic analyses. This regulation has also been highly recommended by related administrations outside the USA.

A postulated aircraft crashing into containment vessels may trigger a series of disasters related to containment capacity including: (1) global and local failure of structures due to transient impact, (2) intensive vibrations propagated from an impact position to the SSCs (structures, systems and components), and (3) fire igniting after jet fuel leakage upon impact (Lo Frano and Forasassi, 2011; IAEA, 2017a,b). Safe shutdown and decay heat removal are also important issues as a consequence of aircraft crash. However, they are out of the study scope and are not investigated in this paper.

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Many efforts have focused on dynamic responses and fire resistance of nuclear containments in aircraft crash scenarios. The transient responses of containments crashed by civil and military aircrafts have been investigated in the past 20 years generally using numerical approaches. These numerical methods fall into two categories: "the force time-history analysis (FTHA) method" and "the missile-target interaction analysis (MTIA) method" (NEI, 2009; IAEA, 2017b). In the FTHA method, the aircraft impact action is represented as a time history function and used as input data to perform a dynamic analysis. This impact force can be obtained experimentally, analytically or numerically. Evidently, a full-scale test is tremendously expensive to perform (Sugano et al., 1993). Hence, analytical approaches, e.g., the well-known Riera function (Riera, 1968, 1980) and numerical simulations commonly based on the finite element method (FEM) are usually adopted with consideration of geometric and material nonlinearity (Jin et al., 2011; Wilt et al., 2011; Iliev et al., 2011; Lee et al., 2013, 2014; Kostov et al., 2014). The obtained impact forces depend on aircraft types and weight, impact velocities, incidence angles and crash positions. In particular, Arros and Doumbalski (2007) applied a simplified model of a "fictitious nuclear building" and compared the effect of using the FTHA and MTIA methods. Comparative results found that the fictitious nuclear building response contained more high frequency content using the MTIA method than that using the FTHA method. In additional, Appendix A presents a summary of the results from some previous studies mainly focused on safety assessment of containment capacities in terms of their global and local failures.

On the other hand, investigations on aircraft-crash-induced vibration of the SSCs are a concern (IAEA, 2017a), even though they have attracted less attention so far and are associated with a heavy computational burden (Rouzaud et al., 2016). Petrangeli (2010) proposed a concept to attenuate the vibration of inner structures by installing seismic-type isolators when the external containment was crashed by aircrafts. In a case study, Kostov et al., (2014) reported a scheme to evaluate equipment safety due to aircraft-crash-induced vibration. This was done by comparing a variety of damage indicating parameters (e.g., cumulative absolute velocities) with their estimated threshold values. However, detailed information about the model they used was not presented. In addition, vibration of the equipment inside buildings adjacent to the containment vessel in case of an aircraft crash is sometimes demanded in practice. However, related studies have not been found in the literature.

For the purpose of fire resistance assessment, Jeon et al., (2012) performed heat transfer and thermal stress analyses of a containment and its auxiliary buildings due to an aircraft crash. They compared the fire-induced section forces of the containment wall with section resistance using the load–moment strength interaction diagram. Results confirmed that the containment could maintain structural integrity against external fire thanks to its relatively thick sections and the thermal properties of concrete. In their study, structural damage due to impact action was not considered.

The above efforts addressed the significant loading conditions (i.e., impact, vibration and fire) that should be considered for the safety assessment of containment capacities against aircraft crashes. However, a systemic assessment procedure taking into account all loading conditions was not found in literature. Hence, a foundational understanding of the complexity of loading conditions and the safety margins of containment vessels is, therefore, unavailable. This paper addresses this information gap by presenting an integrated procedure to investigate the transient response, vibration response, and fire effect of a nuclear containment vessel subjected to a commercial aircraft crash. The containment vessel belongs to the Generation III^{+} NPPs under construction in China for the first time and their structural capacities are of concern. Ground vibration can be used as input data to obtain the vibration of equipment inside the containment or inside buildings adjacent to the containment. A safety assessment in association with transient response and subsequent fire effect is also provided. Unfortunately, a vibration-related safety assessment depends on the performance of individual equipment and, therefore, is beyond the study scope of this paper and is not presented herein. A crash caused by a military aircraft is also beyond the study scope and is not considered.

Two assumptions were adopted in the computation: (1) Interaction among the three loading conditions (i.e., impact, vibration and fire) was not considered; hence their effects were decoupled, and (2) the explosion of aircraft components was ignored. The first assumption was based on the essential differences of time durations among the three loading conditions. The transient impact process usually lasted less than 0.5 s (Iliev et al., 2011). The vibration attenuated in seconds while the fire burned for tens of minutes before putout.

2. Containment vessel-soil model

An integrated containment vessel-soil model was established based on FEM to investigate the transient response of the containment vessel and subsequently induced ground vibration. The model was composed of a containment vessel model, a soil model including two soil types, an aircraft type of Boeing 767-400, and three impact positions. A separate containment vessel-soil model was not an appropriate option in this case because it indicated uncertainty pertaining to the effect of soil-structure interaction (SSI) on ground vibration. In addition, almost no benefit of numerical efforts could be gained when a separate model was used. Furthermore, auxiliary buildings and inner structures inside the containment vessel were not modeled and their vibrations were unavailable. However, their vibration could be obtained without technical difficulties once they were modeled and incorporated into the model. The model was built using the commercial finite element program ANSYS/LS-DYNA (Hallquist, 2006).

2.1. Profiles of containment vessel and soil

The targeted containment vessel primarily consists of an exterior reinforced concrete (RC) containment vessel (also called a shield building) and an interior steel containment vessel, as shown in Fig. 1. The exterior containment vessel has a total height of 69.6 m and mainly includes a cylindrical wall, conical roof, and a PCS (passive containment cooling system) water tank. The outer diameter of the cylindrical wall is 44.2 m and the wall thickness is 914 mm. The conical roof is composed of an upper RC roof slab and a lower steel supporting system, both of which carry the PCS water tank located on the top of the exterior containment vessel. The roof slab has a uniform thickness of 914 mm. The steel supporting system includes steel girders, connecting beams, and an upper steel slab. In total, 32 steel girders are arranged in a radial direction and connected by 15 secondary connecting beams in a circumferential direction. The PCS water tank is safety related and fully filled with water to cool the nuclear reactor in the event of an accident. The interior steel containment vessel is 44.5 mm thick with a spacing of 1.37 m from the exterior containment vessel. This steel structure accounts only for internal events, which is irrelevant to the external events involved in this study. Both containment vessels were fixed on the basement slab which was constructed using RC with a thickness of 12 m. The concrete compressive and tensile strengths were designed to be 27.6 MPa and 3.26 MPa, respectively. The yield strength, elastic modulus, Poisson's ratio and ultimate tensile strain of the reinforcing steel