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Review

Aircraft impact analysis of nuclear safety-related concrete structures: A review

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A R T I C L E   I N F O

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A B S T R A C T

Safety-related nuclear structures, including concrete nuclear containment vessels, constructed before September 11, 2001, were not purposely designed to resist any impact loading greater than a light aircraft crash. Since 2001, safety of nuclear facilities against a deliberate or accidental large civilian aircraft impact has drawn much attention worldwide. However, current design guides for nuclear structures provide limited information on analysis methodologies for such aircraft impact. This document presents basic general knowledge required to analyze concrete structures for an aircraft impact and provides a summary of available numerical and experimental investigations that may be used to benchmark an aircraft impact simulation. The methodologies available for an aircraft impact analysis are overviewed with an emphasis on structural damage analysis. Constitutive models used for concrete, reinforcing steel, and composite materials are addressed in this paper.

1. Introduction

Since the middle of the 20th century, nuclear power has been one of the key development areas for energy generation and is considered to provide one of the most promising strategies for reducing carbon emissions around the world. As of 2013, there are 437 Nuclear Power Plant (NPP) units in 31 countries in operation, and 68 plants in 15 countries under construction [1]. Despite of the nuclear proliferation, the risk of unforeseen beyond-design-basis events has become a major concern for NPP operators and regulators around the world since the Fukushima accident in 2011. It is noted that nuclear safety-related concrete structures (CS) include containment buildings, shield structures/building, reactor buildings, and other structures with similar functions in this paper.

In the United States, old CS constructed before September 11, 2001, was not purposely designed to resist any impact loading greater than a light aircraft crash which was the accepted design-basis case drawn from the improbability or pure chance of a civil airliner accidentally crashing into a NPP [2]. Accidental large aircraft impact is a beyond-design-basis event, which requires risk evaluation using probabilistic assessment methods as given in DOE Standard [3]. Since the tragic September 11 incident, safety of CS against a deliberate or accidental large civilian aircraft impact has drawn much attention worldwide.

Abbreviations: NPP, Nuclear Power Plant; CS, concrete structures; DOE, department of energy; NEI, Nuclear Energy Institute; IAEA, International Atomic Energy Agency; NRC, Nuclear Regulatory Commission; AIA, aircraft impact analysis; ACI, American Concrete Institute; ASME, American Society of Mechanical Engineers; ASCE, American Society of Civil Engineers; DEM, discrete element method; SPH, the Smooth Particle Hydrodynamic Method; FE, Finite Element; FD, Finite Difference; DIF, Dynamic Increase Factors.

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However, current design guides on nuclear safety-related structures [3–7] provide limited information on analysis methodologies for such aircraft impact. Despite the fact that the NEI guide [8] provides general information on this topic (i.e. regulatory requirements for beyond design basis), it does not include detailed analysis procedures and material models that characterize structural damage. Many numerical studies and investigations on aircraft impact of CS have been conducted so far; however, numerical methods employed for an impact analysis vary from simple to complex. It is difficult for an analyst to make a decision in terms of analysis methodologies, analysis programs, constitutive models, and elements erosion criteria. Therefore, this paper gives an overview of aircraft impact analysis (AIA) methodologies and research findings in this regard, including both experimental and numerical evaluations. A tabular overview of AIA publications with detailed information on the hydrocodes, modeling methods, material models, and failure modes of CS is also provided. Besides, characteristics, advantages, and disadvantages of different AIA methodologies are summarized. The discussions herein are limited to NPP outer CS, designed to house a reactor and primary system components. Methodologies employed for probability risk-based assessments and fire or explosion effects initiated by aircraft fuel are not included in this paper.

2. Basic general knowledge

General knowledge of the following methodology and classifications is critical in order to understand or perform an AIA of CS.

2.1. The Riera methodology

Riera [9] developed a simple analytical formula to approximate the load–time function of an aircraft normal impact against a rigid surface based on the mass, stiffness distribution and buckling load of the aircraft. The Riera's formula has served as a basis for the force–time history analysis presented in Section 4.1. This method is included in the NEI report [8], and is adopted in the DOE standard [3] and other technical documents [7]. However, Abbas et al. [10] pointed out that the Riera formula is based on the gradual crushing of the projectile, which is not realistic and can give much conservative result. They proposed an approach for calculating impact force on the basis of conservation of mass, momentum and energy together with the consideration of certain mode of collapse, and highlighted the error in the evaluation of reaction time response using the conventional approach by considering the impact of a hollow cylindrical missile.

2.2. Hard impact versus soft impact

There two categories of structural impact: soft missile impact (impulsive loading, impulse driven) and hard missile impact (impactive loading, energy driven). Two methods have been primarily proposed to classify soft and hard impacts:

2.2.1. Method I

Eibl [11] classifies the impact as hard or soft based on whether the missile deformability is small or larger relative to the target deformability using a mass-spring model (Fig. 1a). In this figure, the spring, k_1, represents the force resulting from the contact between projectile, m_1, and target, m_2. The spring, k_2, represents the resisting force of target due to the deformation in the target. Two equilibrium equations can be written as follows, where $x_1(t)$ and $x_2(t)$ denote displacement in the projectile and target, respectively.

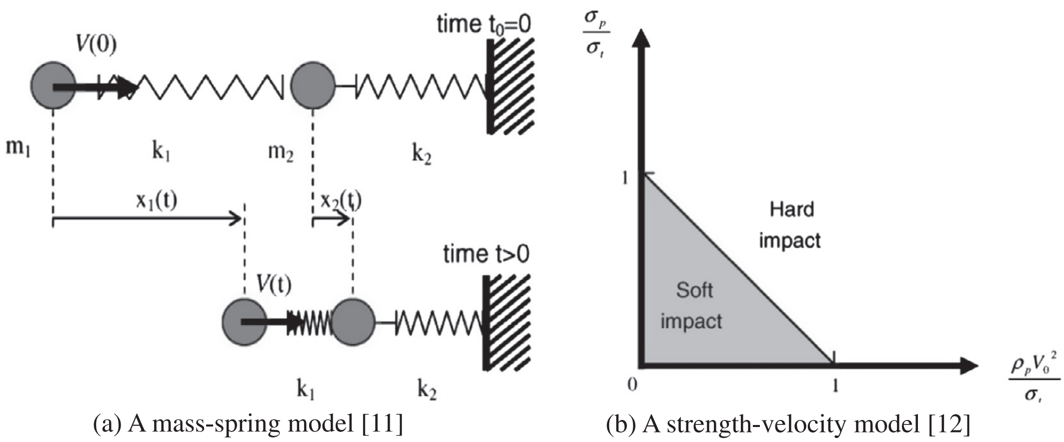

Fig. 1. Characterization of soft and hard impact.