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Some Considerations about the RIERA Approach and Missile-Structure Interaction Analysis Method in Aircraft Impact Assessment on Nuclear Power Plants

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1. Introduction

Studies related to the safety assessment of nuclear power plants crashed by large civil aircrafts have been progressed as the changes of nuclear safety assessment criteria to prove the structural safety of nuclear power plants against large civil aircraft crashes since 2009. The full- scaled experimental tests of large civil aircrafts crashes to nuclear power plants are practically impossible, the safety assessment of nuclear power plants against large civil aircrafts have been accomplished by numerical analysis methods. In this paper, the classically preferred RIERA approach and the so-called missile-structure interaction (MSI) analysis methods which are indebted by the latest computing power are discussed about their inherent discrepancies.

2. Methodologies on aircraft impact assessment

2.1 RIERA Approach Method

RIERA approach method proposed by Prof. Riera [1] begins with the assumption that a flexible body (aircraft) crashes to the flat and rigid wall. First the reaction force time history of the flat and rigid wall is calculated by the sum of the crushing force (P_c) of the impacting aircraft section and the production of mass distribution and velocity during impact. Then, the reaction force time history, i.e., the impact load-time history, so-called the RIERA function is applied to the impacting surface of structure to compute the responses of the structures concerned. Thus, the mass and crushing force distributions are most important in the calculation of the impact load-time function. The most advantage in RIERA approach method is that aircraft model can be replaced by the RIERA curves and there is no need to develop the aircraft model.

Impact load-time histories applied to nuclear power plants for various aircraft models are proposed by many researches. The impact load-time history proposed by Takeuchi [3], of the target aircraft considered in this study is shown in Fig. 1. (Legend: -- Riera(200ton))

As the effects of aircrafts crashes to nuclear power plants are idealized and simplified by the impact load-time histories in RIERA approach method, general nonlinear dynamic analyses are possible. Thus the implicit dynamic analyses ensuring the convergence of solutions can be accomplished and somewhat similar results with respect to a variety of programs or users are expected.

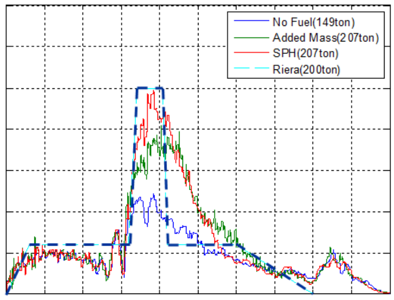


Fig. 1. Proposed and computed impact load-time histories

2.2 Missile-Structure Interaction Analysis

Being indebted by the latest computation power and advances of general purpose finite element programs, the missile-structure interaction analysis methods considering the material, geometric and also contact nonlinearities between two bodies of the nuclear power plants, especially reactor containment building and aircraft modeled by detailed finite elements are the mainstream in the field of safety assessment of nuclear power plants against large civil aircraft recently.

However, it is very difficult to apprehend the aircraft specifications such as dimensions and materials for the special nature of the airline industries (few international companies share the market and almost all items related to specifications are confidential) and it is not easy to make or develop the finite element model of aircrafts exactly as they are.

Currently one of the advanced and detailed finite element models of large civil aircrafts is the aircraft model developed by Applied Research Associate, USA [2]. It is said that the outer shapes of aircraft are created by using the geometry models which are relatively easy to access. Also each material and thickness of aircraft components are based on the actually measured data from aircrafts wreckages.

Thus the numerical model, i.e., finite element models of nuclear power plants and also aircrafts are necessary to accomplish the missile-structure interaction analysis methods in safety assessment of nuclear power plants against large civil aircraft. Fig.2 shows the developed finite element model of large civil aircraft. Also the computed contact force time histories according to various aircraft modeling techniques are shown in Fig.1.

The contact forces between bodies are computed and the structural responses due to these contact forces are sequentially computed by explicit dynamics considering contact nonlinearity between bodies according to the initial conditions such as impact velocity, angle and position in missile-structure interaction analysis. Thus it is not necessary to use RIERA curve and to define the surfaces which the impact load time function must be applied in RIEAR approach.

The time increment values are very small to compute the instantaneous changes of the contact forces, and excessive deformations of structures can occur. For these reasons, the solutions are computed by explicit dynamic analysis, which its stable time increments are very small to ensure the stabilities of solutions. In order to provide the stability of solutions from excessive deformation, sometimes element deletion techniques are possible to remove unnecessary elements. In this case the energy balances must be examined carefully. To include the static responses, transient response analyses are possible but the solutions tend to oscillate.

Fig. 2. Developed finite element model of large civil aircraft.

2.3 Inherent Discrepancies between RIERA Approach Method and Missile-Interaction Analysis Method

The basic assumption of RIERA approach method, which gives an idealized and simplified impact load-time history as the effect of aircraft crashes to structure is that flexible aircraft collide with the rigid wall. The rigid wall was not deformed or damaged at all while the aircraft are deformed and damaged by the reaction force of rigid wall computed as the function of the sum of the crushing force (P_c) of the impacting aircraft section and the production of mass distribution and velocity during impact. However the structure also would be deformed or damaged not like the rigid wall. The entire impact load calculated by RIERA approach method is applied to the structures. This means that the structure itself is subjected to the entire impact load by external force.

According to the fully elastic Hertz model [5] in classical contact mechanics, the maximum contact force of the impact, depicted in Fig. 3, between elastic sphere and half space is a function of the radius, mass of the sphere and elastic modulus of the sphere and half space by following equation (1).

$$F_{max} = mn^{2/5}\left(\frac{5V^2}{4}\right)^{3/5} \quad (1)$$

where,

$$n = \frac{4E^* R^{1/2}}{3m}$$

$$E^* = 1/((1-\nu_1^2)/E_1 + (1-\nu_2^2)/E_2)$$

V : Impact velocity

m , R : Mass and radius of elastic sphere

E_1, ν_1, E_2, ν_2 : Young's modulus and Poisson's ratio of elastic sphere and half space respectively.

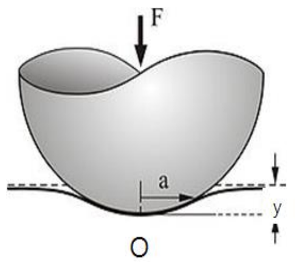


Fig. 3. Impact between elastic sphere and half space.

The maximum contact force is a theoretical solution of differential equations and its value varies with E^* (relative elastic modulus between two bodies). This means that the same sphere with equivalent kinetic energies can produce different contact forces according to the relative elastic modulus. The initial kinetic energy of sphere (projectile such as aircraft) is converted into elastic deformation or strain energies of sphere and half space and restored into kinetic energy of sphere.

$$\mathbf{KE}_{\mathbf{sphere}} \rightarrow \mathbf{SE}_{\mathbf{sphere}} + \mathbf{SE}_{\mathbf{half\ space}} \rightarrow \mathbf{KE}_{\mathbf{sphere}}$$

In the case of high-speed impact which is expected the inelastic behavior beyond elastic range, the initial kinetic energy of the projectile is transferred almost into inelastic deformation energy of the projectile and the target (plastic dissipation energy) and kinetic energy of the projectile (because the residual velocity is zero) is not restored. In particular, in the case of the impact between aircraft and massive structures such as the reactor containment building, the initial kinetic energy of aircraft would be converted to plastic dissipation energy by the destruction of the aircraft. However, since there is no projectile (aircraft), the entire impact load (computed by RIERA approach method) act to the structure and cause the deformation or damage of the structure only. Table I summarized the discrepancies between RIERA approach method and missile-structure interaction analysis method.

Table I: Discrepancies between RIERA approach and MSI

	RIERA Approach	Missile-Structure Interaction
Dynamic Analysis Method	*Implicit *Explicit	*Explicit only
Required Model	*Structure only	*Structure *Aircraft
Computational Cost	*No. of DOFs *Incremental time step	*No. of DOFs *Smallest characteristic element length
Impact Effect	*Impact load time function	*Contact forces during analysis
Nonlinearity	*Material *Geometry	*Material *Geometry *Contact
Energy Balances	*Structure	*Structure *Aircraft
Kinetic Energy	*NA	*Aircraft
Strain Energy	*Structure only	*Structure *Aircraft
External Work	*YES	*NO

3. Applications: Reactor Containment Building

3.1 RCB Models

Typical type of reactor containment building shown in Fig. 4 is chosen in this study. Fig.4 shows the pre-stressing tendons, reinforcement bars and concrete structure models of finite element analyses. Three dimensional embedded truss elements for reinforcement bars and pre-stressing tendons are used and three dimensional solid elements for concrete structure are used in finite element modeling.

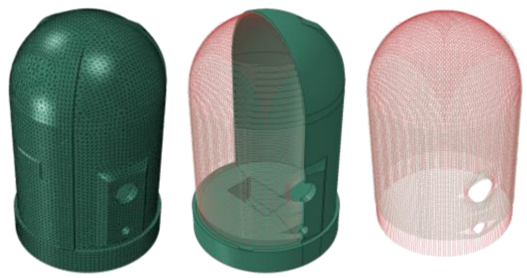
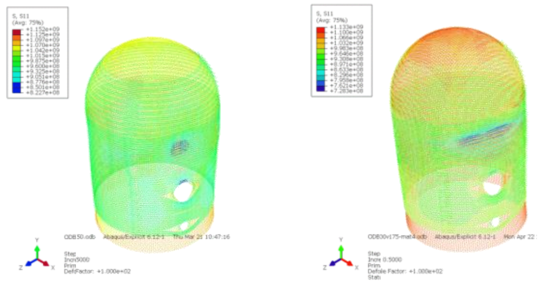


Fig. 4. FE model of reactor containment building concrete body, horizontal and vertical tendons.

3.2 Responses

Typical responses such as displacements and their space and time derivatives such as accelerations, stresses are computed by RIERA approach and missile-interaction analysis method. Fig. 5 shows tendon stress distributions for each method. The maximum value of impact load-time history is approximately 1.25 times as shown in Fig. 5. And the impact area for RIERA approach is assumed by circle while the contact surface computed during the missile-structure interaction analysis resembles the shape of aircraft fuselage and wings. Therefore the stress distributions shown in Fig. 5 are different form each other.



RIERA Approach Missile-Structure Interaction

Fig. 5. Tendon stress distributions for each method.

3.3 Energy Balances

The conservation of energy implied by the first law of thermodynamics states that the time rate of change of kinetic energy and internal energy for a fixed body of material is equal to the sum of the rate of work done by the surface and body forces [6]. From this notation, the energy balance (ETOTAL) is as follows:

ETOTAL=ALLKE+ALLIE+ALLVD+ALLFD–ALLWK

where, ALLKE: kinetic energy, ALLIE: internal energy, i.e., total strain energy, ALLVD: viscous dissipation, ALLFD: frictional dissipation, ALLWK: external work.

The energy balance of the system could be said to be maintained, if the total energy was close to zero, which meant that few energy appeared or disappeared from the system. Also internal energy ALLIE is sum of the following energies:

ALLIE=ALLSE+ALLPD+ALLAE+···

where, ALLSE: recoverable strain energy, ALLPD: energy dissipated by plastic deformation, ALLAE: "Artificial" strain energy.

Fig. 6 show energy balances for RIERA approach method. The initial internal energy with value of 472 (MJ) is due to the pre-stressing effect. Most of internal energy by pre-stressing is stored in the horizontal and vertical tendons. All energies due to the RIERA curve are converted into the internal energy of reactor containment building. Fig. 7 show energy balances for missile-structure interaction analysis method. The initial kinetic energy of aircraft with value of 2330 (MJ) is dissipated (disappeared) by the destruction of aircraft. And the internal energy of whole system (i.e., the reactor containment building and aircraft) is increased to 2230 (MJ). And viscous dissipation energy (ALLVD) is increased to 422 (MJ), while this phenomenon does not occur in RIERA approach method. Finally the internal strain energies of reactor containment building excluding tendons are compared in Fig. 8. Table II summarized balance of energies for each method.

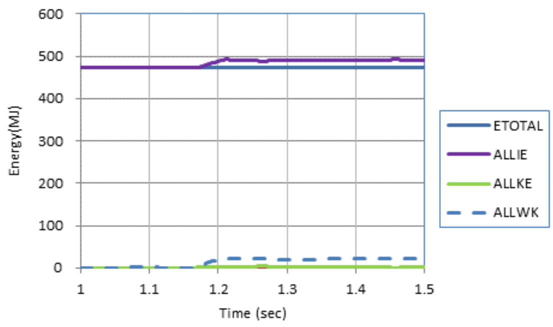


Fig. 6. Energy balance histories for RIERA approach method.

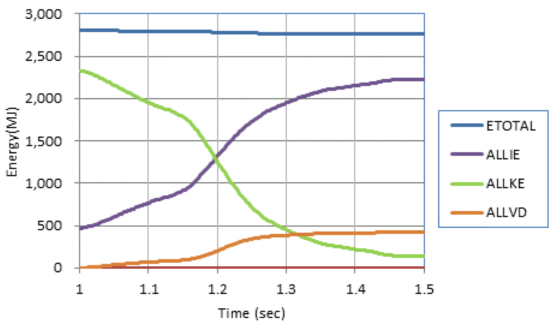


Fig. 7. Energy balance histories for missile-structure interaction analysis method.

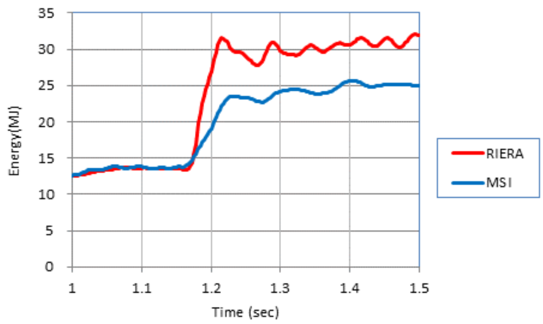


Fig. 8. Comparison of internal strain energies of reactor containment building.

Table II: Balance of energies (unit: MJ)

Energies	RIERA		MSI	
	t=0s	t=0.5s	t=0s	t=0.5s
ALLKE	0	2	2330	137
ALLIE	472	491	472	2230
ALLWK	0	21	0	0
ALLVD	0	0	0	422
ETOTAL	472	472	2800	2770

4. Conclusions

Studies on the safety assessments on the nuclear power plants against large civil aircraft crashes are ongoing actively. In this paper, the classically preferred RIERA approach and the so-called missile-structure interaction (MSI) analysis methods are discussed about their inherent discrepancies especially from the point of view energy balances. More advanced and simplified ways in the safety assessment of nuclear power plants against large civil aircrafts may be possible by understanding the inherent discrepancies of the RIERA approach method and the missile-structure interaction method and reducing the differences of structural responses.

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