Budapest University of Technology and Economics

Characteristic parameters of aircraft impact into robust engineering structures

Summary and theses of PhD dissertation

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1. Introduction

1.1. Motivation

Analysing the consequences of potential aircraft impact into engineering structures is an issue of high importance. Probability of an accidental aircraft crash is low, but the consequences can be extremely severe (IAEA (International Atomic Energy Agency) Safety Guide, 2003; DOE (U.S. Department of Energy) Standard, 2006; NEI (Nuclear Energy Institute), 2011). Therefore, the analysis of impacts is included in the design basis of high importance structures such as nuclear power plants (NPPs). Moreover, terrorist attacks have also increased the actuality of this field of research since September 11, 2001.

The topic has a wide background in the literature, but there are open questions that need to be answered. One of the most important aspects is the global understanding of the phenomena that occur during an aircraft impact. Due to increasing computational capacity, more and more complex models are applicable to analyse one or more aspects of the impact (structural response, behaviour of concrete material, explosions, fire, etc.). These computational techniques are efficient, however, the large number of parameters that appear in the models can cause high uncertainties. It is not obvious to see the role, importance and connections of different parameters. In my PhD thesis, I aim to find the most important parameters and analyse their effect on the course of the impact and, by this, to contribute to the better understanding of the aircraft impact phenomenon.

1.2. Effects of an aircraft impact

An aircraft impact can cause various types of failure. According to the IAEA Safety Guide (2003), global and local primary effects, vibrations and secondary effects (fire, explosion, etc.) have to be examined. Global effects include the overall response of the entire structure (collapse, overturning, excessive structural deformations and displacements), while local effects (penetration, perforation, scabbing, spalling, etc.) occur in the vicinity of the impact zone (see Fig. 1). In the dissertation, both global and local primary effects are discussed.

The damage caused by the aircraft or its parts to a great extent depends on the stiffness and rigidity of the missile and the target. Usually, an aircraft fuselage that impacts a rigid concrete structure with thick walls implies a deformable (soft) missile causing global effects (Sugano et al., 1993-1), while the engine can be considered as a non-deformable (hard) missile that penetrates into or perforates the structure (Sugano et al., 1993-2,3). In general, different models and methods are used for the analysis of global or local effects, therefore, in the dissertation we also discuss them separately.

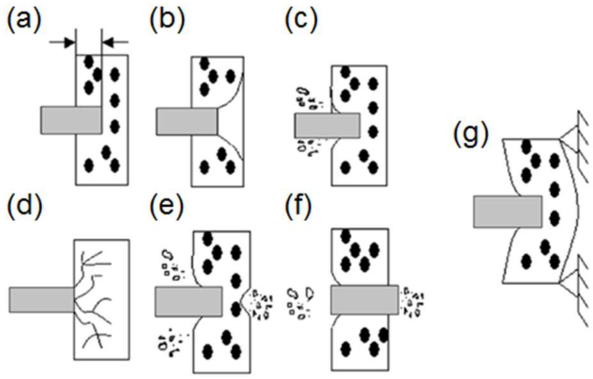

Fig. 1: Local effects: (a) penetration, (b) cone cracking, (c) spalling, (d) cracks, (e) scabbing, (f) perforation and global effect (g) of missile impact (Li et al., 2005)

For the analysis of global structural response, two methods are suggested by the Nuclear Energy Institute (2011): the force time-history analysis (FTHA) and the missile-target interaction analysis (MTIA). In the first method (FTHA), the aircraft appears as a time-dependent load that acts on the target structure, while in the second one (MTIA) the aircraft and target appears in a detailed, coupled model.

The load-time (reaction force-time, $F(t)$) function for FTHA can be determined by several models in which normal impact and perfectly rigid target are typically assumed. The Riera model (Riera, 1968) is the most widely used method to determine the reaction force that acts on a perfectly rigid wall during normal impact of a rigid—perfectly plastic aircraft. In our analysis, we also apply the Riera model and compare its results to finite element (FE) model results.

Concerning local effects, the most important quantities that characterize an impact are the penetration depth (x_p), perforation limit (e) and scabbing limit (s). Penetration depth is the distance to which the nose of the missile penetrates into a very thick target (infinite half-space). Perforation and scabbing limits are the minimum needed thicknesses to prevent perforation or scabbing, respectively. These values are typically determined by analytic and semi-empirical formulae (Kennedy, 1976; Teland, 1998; Li et al., 2005; and Murthy et al., 2010).

1.3. Objectives of the dissertation

The main objective of the dissertation is to provide better understanding of the course of aircraft impact into relatively rigid engineering structures. Both global effects of soft impacts (when deformations of the target are negligible compared to deformations of the missile) and local effects of hard impacts (when deformations of the missile are negligible compared to deformations of the target) are analysed and the role and importance of different parameters and parameter combinations are examined both in the well-known Riera model and in FE models.

The most important questions that we aim to answer are the following:

Concerning global effects of a soft impact:

1. Which are the important parameters and parameter combinations of the Riera model that characterise the course and outcome of an aircraft (soft missile) impact?
2. Is the assumption of a perfectly rigid target in the Riera model conservative?
3. Does the importance of the relevant parameter combinations depend on the model applied?
4. In what range of the parameters do the Riera and the FE models give similar results?
5. What is the consequence of real aircraft fuselage parameters and shape, including nose and tail as well as wing and engine, on the course of the impact?

Concerning local effects of a hard impact:

6. How do different input parameters and parameter combinations affect the local failure modes (penetration, perforation) that occur during impact of a hard missile into a relatively softer but massive structure?

2. Parametric study of the Riera model

Our main goal was to find the important parameters that characterise the global structural response during an aircraft impact. Therefore, a systematic parametric study of a simplified (uniform) aircraft (cylindrical rod) was carried out. For the analysis of the uniform aircraft fuselage, we followed the assumptions of the Riera model (Riera, 1968).

In the Riera model the aircraft, impacting the target in normal direction, is assumed to be a deformable missile of rigid–perfectly plastic material, and the structure is assumed to be perfectly rigid. It is also assumed that the aircraft crushes only at the cross-section adjacent to the target. Therefore, at time t after the start of the impact, the missile consists of two parts: an uncrushed part of length $x(t)$ and of mass $m(t)$, and an infinitesimally small part of mass

(−*dm*) > 0 that crushes in the next time instant, see Fig. 2(a). The impact (reaction) force to be determined is *F*(*t*), while the force acting between the intact and the crushing parts is the crushing force *P*(*x*) which depends on the length *x*(*t*) which is the actual intact length of the aircraft.

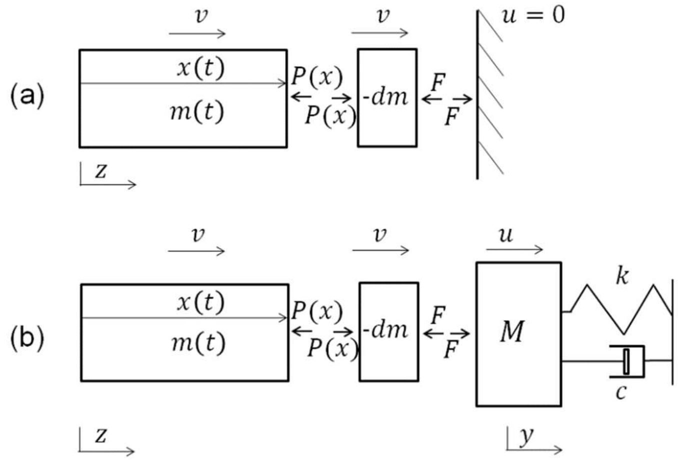

Fig. 2: (a) Original and (b) elastic Riera model

This model has been extended by Wolf (1978) to include a one degree-of-freedom, damped, elastic system modelling the flexibility of the target, see Fig. 2(b). The (modal) mass of the target is *M*, the spring constant is *k*, the damping coefficient is *c*.

In order to find the most important combination of parameters, the governing equations of the Riera model that are based on balance of momentum equations of the intact and instantaneously crushing part of the aircraft were cast into a dimensionless form.

For the simple case of a uniform aircraft fuselage (cylindrical missile) and rigid structure we derived an analytical solution. In this case, the course of the impact depended only on the *damage potential D*, which is a dimensionless parameter we defined as:

$$D = \frac{\frac{1}{2} m_0 v_0^2}{L P_0}, \tag{1}$$

where m_0, v_0, L, P_0 are the total mass, initial velocity, total length and characteristic crushing force of the aircraft, respectively. This dimensionless parameter is the ratio of the kinetic energy of the missile to the work required to crush it.

For elastic target structures, we also found that the course of the impact mainly depends on the damage potential, neither the ratio of the aircraft mass to that of the target structure nor the ratio of the target's stiffness to the crushing force of the aircraft affected the course of the impact significantly. However, target elasticity could influence the maximum value of the reaction force, which could be higher than the maximum reaction force in case of a rigid target. This means that the rigid target assumption is not always conservative. The parameter combinations that caused the maximum target deformation and maximum reaction force have also been determined. These findings lead to the following theses:

Thesis 1 *Based on the dimensionless form of the Riera model, I derived explicit formulae both for the course of the impact and for the reaction force acting on the target in case of a uniform aircraft fuselage (cylindrical rod) impacting a rigid target.*
Based on (Laczák and Károlyi, 2017-1)

Thesis 2 *Based on the Riera model, I carried out a systematic parametric study of a uniform aircraft fuselage (cylindrical rod) impacting rigid or one degree-of-freedom elastic targets and found that the only relevant combination of the parameters that defines the course of the impact is the damage potential defined as the ratio of the initial kinetic energy of the missile to the work required to crush it.*
Based on (Laczák and Károlyi, 2017-1)

Thesis 3 *In the Riera model, extended to one degree-of-freedom elastic targets, the elasticity of the target affects the maximum value of the reaction force, which can be higher than the maximum reaction force in case of a perfectly rigid target. This result proves, that application of perfectly rigid target for the computation of the impact force is not always conservative.*
Based on (Laczák and Károlyi, 2015; Laczák and Károlyi, 2017-1)

Thesis 1 helps to better understand the commonly applied Riera model extended to elastic targets and provides a possible benchmark to validate numerical codes. Thesis 2 sheds light on the specific role of the newly defined *damage potential,* that governs the course of the impact in case of uniform fuselages analysed by the Riera model. In practice, reaction force—time functions applied to different models of the target as time dependent loads are typically determined by rigid target assumption. In Thesis 3, we proved that this assumption is not always conservative, therefore, cannot be applied automatically.

3. The role of the damage potential in a finite element model of soft impacts

In order to clarify the importance of different parameters, we made a step back, neglected the effects of real aircraft geometry and investigated the simplest case of a uniform missile by the widely used Riera model.

Next, we took a step forward and investigated a model of aircraft impact using more parameters than the Riera model to see if the sole dependence on the damage potential remained. The model we constructed was a FE model of a uniform (cylindrical) aircraft fuselage impacting either a rigid or an elastic target (Fig. 3). The model was built in ANSYS Workbench Explicit Dynamics environment (Ansys Workbench Help, 2015). The uniform fuselage used in the FE simulations was a hollow cylinder with parameters characteristic for a small fighter jet, like Phantom F4. For the fuselage, we assumed a simple linearly elastic–quasi perfectly plastic material. In the model, finite elements are deleted if a pre-set ultimate strain is reached.

The model contained much more parameters than the Riera model used in the previous analysis, but it still contained less parameters than a full-scale simulation of a real aircraft impact. The reduced number of parameters made it possible to identify which parameters or parameter combinations had important effect on the course of the impact. Our main finding was that the damage potential had the major effect on the course of the impact, remained valid. The multitude of parameters in the FE model had only a secondary effect on the impact. We also found that if the parameters were varied so that the damage potential remained the same then the course of the impact remained similar.

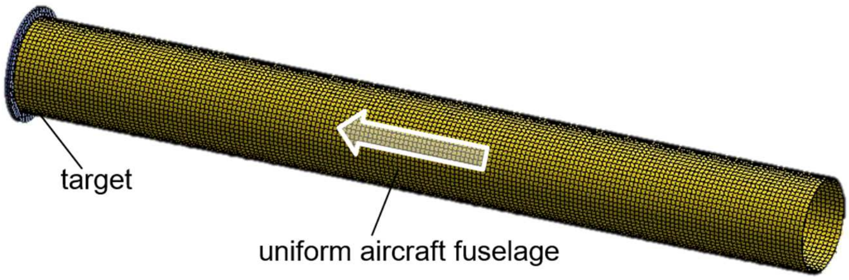

Fig. 3: FE model of uniform aircraft fuselage and rigid target plate

The results lead to the following two theses:

Thesis 4 *In a wide range of parameters, I compared the results obtained from the Riera model to those obtained from a finite element model of a uniform, quasi rigid–quasi perfectly plastic aircraft fuselage impacting rigid or linear elastic targets. I found that, within the examined parameter range, the damage potential is the most important parameter that determines the course of the impact. This means that,*

– if the parameters of either the missile or the target are altered in a way that the damage potential remains the same, or

– if parameters that only appear in the finite element model are altered,

then the course of the impact remains similar.

Based on (Laczák and Károlyi, 2017-2)

Thesis 5 *The difference between the results of the Riera and finite element models for the impact of a uniform, quasi rigid–quasi perfectly plastic aircraft fuselage depends on the value of the damage potential D. If D<2 then hard impact occurs, therefore, the local effects are dominant and both models are out of range of soft impacts. If D is between 2 and 10 then slight or negligible decrease in velocity is visible in the FE model, while there is an intense deceleration in the Riera model, which implies a marked difference between the reaction forces predicted by the two models. If D is high (D>10), then the difference between the Riera and the FE model results becomes quasi-constant. In this region, the deceleration obtained from both models is negligible, and a quasi-hydrodynamic impact occurs.*
Based on (Laczák and Károlyi, 2017-2)

Thesis 4 strengthens the observations of Thesis 2: the crucial role of the damage potential is also valid in our applied FE models. In Thesis 5, the effect of the damage potential on the behaviour of the Riera and our FE models are detailed. In the regime, where difference between the results of the Riera and the FE models are high (*D* between 2 and 10), the models have to be applied with caution, application and comparison of different models are suggested. This critical regime corresponds to cases where intense deceleration of the uniform missile occurs in the Riera model, but does not occur in the FE models. Limits for applicability of the different models and limit values of the damage potential for different impact types (hard, soft, quasi-hydrodynamic) are also set.

4. Effects of realistic aircraft profiles

Effects of real aircraft profiles were examined in two steps: at first the uniform aircraft fuselage was extended by nose and tail, then in the second step, by wings and engines. For uniform aircraft fuselages, the damage potential *D* proved to be the parameter that governed the course of the impact, therefore, its concept was applied to non-uniform aircraft profiles. The effects of the damage potential and of other parameters were analysed by the Riera model and by FE models (Figs. 4 and 5).

The obtained results lead to the following thesis:

Thesis 6 *Using the Riera and a finite element model, I carried out a parametric study of a simplified aircraft fuselage with realistic nose, tail, wing and engine profiles. I found that, similarly to uniform missiles, the damage potential also characterizes the impact in case of fuselages with nose, tail, wing and engine profiles.*
Based on (Laczák and Károlyi, 2014; Laczák and Károlyi, 2017-2)

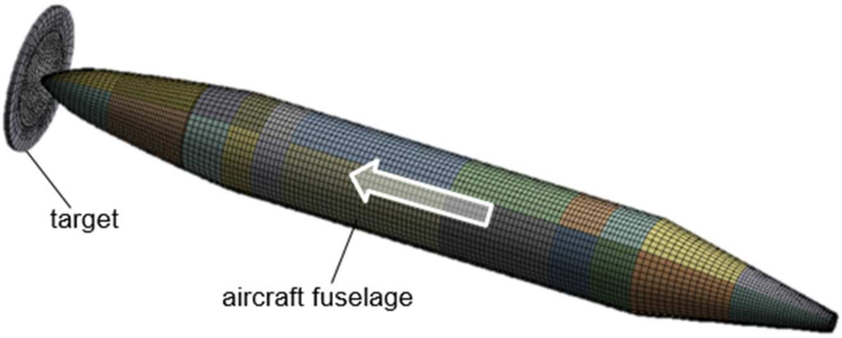

Fig. 4: FE model of aircraft fuselage with nose and tail

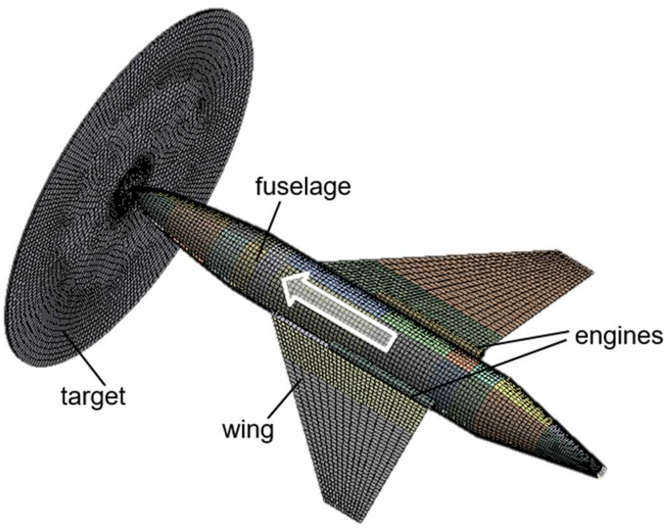

Fig. 5: FE model of aircraft

As stated in Thesis 6, in case of more realistic aircraft profiles the damage potential remained the most important parameter that characterizes the impact. Differences between the Riera and FE model results were similar in case of uniform missiles and more realistic aircraft profiles. The limits of applicability of the models also turned out to be similar in case of uniform missiles and realistic aircraft profiles, which means that the conclusions drawn for uniform missiles can be applied for realistic aircraft profiles too. This shows the general applicability of the damage potential as the parameter that characterizes the impact.

5. Local effects of hard missiles

In the first part of the dissertation, we analysed the parameters of a soft aircraft impact causing global effects to the target structure. Next, we discussed the local effects of (perfectly) hard missiles generated during an aircraft impact or during other accidental events (tornado, turbine crash, etc.). The effect of various parameters on local damage (penetration, perforation) of concrete targets were analysed by commonly applied semi-empirical formulae and by a numerical test series. The well documented real experiments of Sugano et al. (1993-2,3) were used for the verification and calibration of our FE model. Based on the results of a wide range parametric numerical study, new empirical formulae were introduced for the calculation of penetration depth and of the perforation limit. A simple heuristic theoretical model was also presented that supports our new formulae.

Our model was created in ANSYS Workbench Explicit Dynamics FE program and contained a commonly applied multi stage material model for concrete (Concrete 35 MPa) that could follow the failure modes during penetration, perforation and scabbing (Fig. 6).

The most important parameters of hard impact into concrete structure (missile size, mass, impact velocity, concrete strength) were examined. The new semi-empirical formulae for penetration and perforation are dimensionless, general formulae that are practically applicable. Their results are close to results of our FE simulations and to real experimental results. They follow the dependency of penetration depth and perforation limit on the different parameters of the impact of small, medium size and large hard missiles. They are also supported by a simple heuristic theoretical model that is also included in the dissertation.

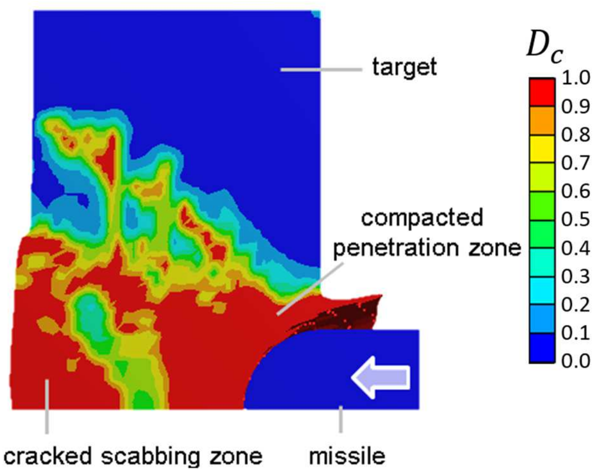

Fig. 6: Damage of concrete target in the FE model. Red colour represents the totally damaged elements (level of damage, D_c=1), blue colour shows the intact parts (D_c=0).

Our findings lead to the following thesis:

Thesis 7 *I built, calibrated and verified a finite element model for hard missiles with spherical nose impacting a concrete target. Based on parametric numerical test series I introduced new semi-empirical formulae to connect the penetration depth, perforation limit to the input parameters of the impact (size, mass and impact velocity of missile, and strength of concrete target). According to the formulae, the penetration depth is proportional to the square root, the perforation limit to the cubic root of the dimensionless impact factor.*
Based on (Laczák and Károlyi, 2016-2)

6. Proposals for further research

In the dissertation, global and local primary effects of aircraft impacts were separately analysed. This separate analysis is common in practical applications, therefore, our planned future work related to impact analyses follows two different directions.

Concerning soft impacts, application of different numerical techniques (discrete element modelling, smooth particle hydrodynamics) and analysis of the effect of different parameters on the outcome of the impact are planned. These analyses, in comparison to the Riera and FE model results, can lead to further conclusion on the applicability of different modelling techniques and on the role of different parameters and their combinations.

In further work concerning hard impacts, we aim to examine the effect of further parameters on the local damage of concrete targets. The numerical model for hard impact shall be extended by steel reinforcement that makes the analysis of scabbing possible. Beside the numerical model, real small-scale experiments are also planned to examine the effects of concrete composition (type and size of aggregate, water-cement ratio, etc.) on the resistance against penetration and perforation. An impact test series has already been executed (Laczák, 2017-3) on concrete panels with different aggregate types.

Detailed numerical analysis of semi-hard missiles (such as real aircraft engines) is also planned. Furthermore, by the development of numerical techniques, combined analysis of global and local effects extended by the examination of secondary effect (explosion, fire, secondary missile formation, etc.) also becomes possible. Among long term plans, the study of such combined analyses is also included.

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