Advances in the analysis of NPP and other critical structures subjected to aircraft impact

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1. Introduction

- The determination of the risk of failure of critical NPP structures subjected to aircraft impact was initially performed by means of a decoupled analysis, in which the forces induced by an incoming projectile impacting against a rigid target, assessed in an initial step, were applied on the target structure in a second, independent step, to evaluate its response.

- Various approaches were later proposed to account for the influence on the interface forces - between projectile and target structure - of motion of the latter. An extensive body of both experimental and theoretical research was directed to the verification of the predictions of the available models and the assessment of model error.
1. Introduction

- As the capacity of available hardware increased, coupled analysis of both aircraft and structure became feasible, which eliminated the need to assess the influence of motion of the target structure on the interface forces. This approach, illustrated by examples in Section 3, is more expensive and cannot be easily incorporated in codes or regulations.
1. Introduction

On the other hand, while predictions of the structural response for impact loading that do not result in significant structural damage may be expected to be characterized by uncertainty levels usually admissible in dynamic analysis, the same statement is not valid in cases of large damage or partial failure. Recent round robin projects suggest that in these cases prediction errors of the response may largely exceed engineering tolerance. The uncertainty is attributed to factors such as the inappropriate choice of material model, which in reinforced or pre-stressed concrete structures should account for fracture, size and rate effects. Finally, recent research on these factors is briefly reviewed.
The US NRC (ex-AEC) requested in 1968 a safety evaluation of the Three-Mile Island (Unit 1) NPP against an accidental aircraft impact, on account of the plant proximity to Harrisburg Airport. The potential effects of fire were also assessed and adequate protective measures taken, although no verification of impact-induced vibrations of equipment was performed at the time (Gilbert Assoc. Inc., 1968).
For purposes of structural analysis, the problem was uncoupled. The time dependent reaction $F_x(t)$ of a flat rigid barrier against a normally impacting aircraft was evaluated first, in order to be applied to the target structure in a second, independent step (Riera, 1968). Assuming a rigid-perfectly plastic behavior of the projectile (aircraft) and zero residual velocity after impact, it was shown that:

$$F_x(t) = P_c \left[ x(t) \right] + \mu \left[ x(t) \right] V^2(t)$$
in which \( V(t) \) denotes the velocity of the projectile and \( x(t) \) the distance from the tip of the projectile:

\[
x(t) = \int V(\xi) \, d\xi
\]

The lower and upper integration limits are 0 and \( t \), respectively, while \( P_c[x(t)] \) and \( \mu[x(t)] \) define the crushing strength and the mass density per unit length of the projectile at location \( x \).
The approach is applicable to structures that do not undergo large displacements as a consequence of impact and was applied by Drittler and Grüner (1976) to determine the forces induced by a Phantom jet aircraft crashing at 215m/s on a rigid target. A simplified load vs. time diagram based on this analysis was subsequently adopted in Germany as a standard requirement in NPP structural design.
As a consequence of these developments, considerable effort was directed to the assessment of the load diagram and the influence of various factors, such as the target displacement. If the impact point displacement $x_a(t) \neq 0$, then equation of the simplified model should be replaced by:

$$F_x(t) = P_c [x(t) - x_a(t)] + \mu [x(t) - x_a(t)] [V(t) - \dot{x}_a(t)]^2 - m(t) \ddot{x}_a(t)$$
Dots denote derivatives with respect to time and $m(t)$ is the crushed mass of the aircraft at the impact point. Riera (1980, 1982) examined the influence of the impact angle in relation to the normal to the surface and the effect of sliding along the surface during the crash. Next figures show the reactions induced by impact of a Phantom jet determined by the simplified model and by Drittler and Grüner (1976), as well as the reactions computed for impact at a $30^\circ$ angle with the normal.
INTERFACE LOADS IN AIRCRAFT IMPACT

J.D. Riera / Nuclear power plant safety against aircraft impact
In the 80’s, there was growing concern with the vibrations induced on the reactor and other critical components by an aircraft impact against the containment building (Riera, 1982). This would require the determination of floor response spectra, similar to those introduced earlier in seismic design. The displacements of the structure at the impact location and induced local damage, which exert marginal influence on the verification of the strength of the target structure, may have a significant effect on induced vibrations.
INCIDENT PRESSURES DUE TO BLAST
Experimental verification of the predictions of impact loading was deemed essential and led to a testing program conducted in Meppen, Germany, in which 6m long steel tubes were launched against instrumented reinforced concrete plates. A parallel series of experiments were conducted at the Winfrith site in England, employing 1:10 reduced scale models of the projectiles used in Meppen. Next figure shows a detail of the Winfrith projectile.
INTERFACE LOADS IN AIRCRAFT IMPACT

Dimensions of UK AEC experimental missile.
INTERFACE LOADS IN AIRCRAFT IMPACT
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![Graph showing interface loads over time with different load types: Exper. Mean, FEM (Explicit int.) and Riera ap.](image)
A comprehensive summary of developments in this area until 1989, as reflected in SMiRT Transactions, was presented during SMiRT 10 and is partially reproduced in Table 2.1. As a consequence of these research efforts, the assumptions introduced in 1968 concerning the so-called *soft* behavior of both military and commercial aircraft, which for unyielding targets results in ideally plastic impact, were firmly consolidated and became the standard approach for analysis and design of NPPs (NEI 07-13, Revision 7, 2009).
INTERFACE LOADS IN AIRCRAFT IMPACT

- The author is not aware of any attempt to statistically quantify model error in the assessment of loads induced by aircraft impact on NPP structures, i.e. the contribution of the model adopted by the designer to total uncertainty, but it should be emphasized that it is not large, being comparable to model error in any standard structural dynamics problem. In terms of the peak of the mean reaction vs. time function, it is suggested that the coefficient of variation of model predictions is of the order of 0.05.
In this connection, the experimental determination performed at SANDIA Laboratories of forces induced on a massive concrete block by a Phantom aircraft impacting at 215 m/s (von Riesemann et al, Muto et al, 1995) must be mentioned at this point. The carefully planned and conducted test, employing a full-scale aircraft at the design flying velocity, led the authors to conclude that “the analysis and evaluation gave an accurate impact force-time curve under the test conditions and confirmed that the existing Riera approach with slight modifications is a practical way of evaluating the impact force”.
It is thus quite clear that, in view of the Meppen, Winfrieth and SANDIA experiments, no major uncertainty remains in connection with the model to determine the interface reaction, although by precaution it is always advisable to accept that there is some inherent uncertainty in the procedure. The previously suggested 5% coefficient of variation to account for model uncertainty in this case appears to be a reasonable value.
To illustrate this point, let us examine next figure, reproduced from Muto et al (1995) which shows the distribution of the crushing strength $P_c(x)$ of the Phantom admitted by Drittler and Grüner (1976) and by Zorn et al (1981) in their assessments of the load-time function, jointly with the distribution inferred by Muto et al (1995) from the measured reaction, which is also affected by large experimental and numerical errors. The uncertainty concerning the crushing load is not negligible, although it plays a small influence because the velocity term is predominant for the range of impact velocities of interest.
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Fig. 9 Comparison of Crushing Loads

Fig. 10 Crushing Load $P_C$ Component in Total Impact Force ($\alpha=0.9$)
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- From (Henkel et al, 2009).
The model of a Boeing B747 aircraft, briefly described above, was coupled in ensuing studies with a complete FEM model of a NPP containment building [Henkel et al (2009) and Risk Engineering (2009)]. Such analysis typically involves several millions DOF models, implying high computing costs as well as great pre- and post-processing design efforts. On the other hand, a global analysis presents advantages, by freeing the analyst from the need to make difficult decisions in the development of the model to reduce its size without losing precision and/or information.
COUPLED AIRCRAFT-TARGET IMPACT ANALYSIS
A large model, with 2.3 million nodes, was recently used by Kirkpatrick et al. (2009) to determine the nonlinear dynamic response of the World Trade Center (WTC) Tower 1 to aircraft impact. Top and side views of the coupled aircraft-target model at the time of initial contact are shown first, while next figure presents top views of the positions of nodal points at the building elevation where impact took place, at various times (0s, 0.2s and 0.5s) from the initiation of impact. The analysis was performed using LS-Dyna Computer Code on a cluster of twelve 2.8 GHz Intel Xeon Processors with a run time of approximately two weeks.
COUPLED AIRCRAFT-TARGET IMPACT ANALYSIS
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Various numerical techniques were tested, leading to the adoption of SPH to model fuel in the global impact analysis due to computational efficiency. Comparisons of predicted and observed response, in particular damage distribution, suggest a close agreement, but since it was not a blind analysis, it is difficult to extend this conclusion to typical design situations. The issue will be addressed again later.
It is clear now that for predicting the response up to failure of solids subjected to dynamic loads, in particular post-peak response, methods based on Continuum Mechanics present disadvantages in comparison with discrete models of the solids under consideration.

This is a consequence of material fracture, which introduces discontinuities in the displacement functions that are difficult to handle in a continuum formulation and fostered the rapid development of more efficient methods of analysis.
Among various such alternative methods, the so-called truss-like Discrete Element Method (DEM) proved quite useful. The approach was proposed by Riera (1984) to determine the dynamic response of plates and shells under impact loading when failure occurs primarily by shear or tension, which is generally the case in concrete structures.
The Discrete Element Method (DEM) is based on the representation of a solid by means of an arrangement of nodal masses linked by elements able to carry only axial loads. The discrete elements representation of an orthotropic continuum was adopted to solve structural dynamics problems by means of explicit direct numerical integration of the equations of motion. Each node has three degrees of freedom, corresponding to the nodal displacements in the three orthogonal coordinate directions.
STRUCTURAL RESPONSE: THE DEM APPROACH
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(a) Stress-strain law for concrete in tension and (b) notation in DEM analysis
A detailed model of the lateral plate of a NPP impacted by a Boeing 747 aircraft shown next was analyzed for the loads corresponding to different velocities and fuel mass assumptions. The DEM model incorporated all reinforcing bars in the plate, including stirrups, and intended to examine the local response of the plate, in order to assess predictions of the global response obtained with a FEM analysis by Henkel and Klein (2007), Henkel et al (2009) and Risk Engineering (2009).
Front view of the impacted plate showing the loaded areas, damage in concrete and yielding steel rebars for one of the loading assumptions.
STRUCTURAL RESPONSE: THE DEM APPROACH

- Maximum normal displacements along plate centerline according to Global FEM and local DEM models
Incipient punching-through failure in one of the loading cases analyzed. In the figure, only the position of the nodes is shown. Actually the two regions remain connected by steel rebars.
Under impact, blast and other short duration loadings, it has long been acknowledged that the strength of engineering materials tends to increase with the loading or the strain rate. In DEM applications, the authors have noticed that simulations conducted on samples of fragile, inhomogeneous materials subjected to various loading conditions, tend to fail under increasing loads when the loading rate increases.
The issue raised a number of questions, such as the need to explain the capacity of the DEM to predict, at least approximately, the increase typically observed in load-carrying capacity of structural systems subjected to impact and blast loadings, the need to assess the correlation with experimental results under different loading conditions and, last but not least, to critically examine the experimental evidence for very high strain rates available in the technical literature.
STRUCTURAL RESPONSE: THE DEM APPROACH

Envelopes of experimental observations of the dynamic/static strengths ratio ($\eta$) for concrete in uniaxial tension (Malvar and Crawford, 1998 and Cotsovos and Pavlovic, 2008) in black lines, and in continuous blue line DEM prediction (from Miguel et al., 2012).
STRUCTURAL RESPONSE: THE DEM APPROACH

- Experimental set-up of the split Hopkinson bar (from Brara and Klepaczko, 2007).
DEM predictions of the rupture configurations at $t = 1.89 \times 10^{-4}$s for impulsive loads amplitudes of 20kN (above), 40kN (center line) and 80kN (below), for simulated sample 1 (left), sample 2 (center column) and sample 3 (right).
A surprising prediction of simulation studies was the detection of *strain rate effects*, that is, the *computed* strength of structural elements was observed to increase as the loading or strain rates increase, *without any change in the constitutive equations or material parameters*. Studies were then aimed at determining the response of cubic samples subjected to controlled displacements, which confirmed the capacity of the DEM to predict the experimentally observed strength increase with the strain rate. However, this conclusion is limited to strain rates smaller than about 1/s.
Hence, modified split Hopkinson bar published test results were simulated next, employing the DEM formulation, which was able to reproduce the observed failure configurations, but in contradiction with published results in the technical literature, do not predict large tensile strength increases \((\text{ratios } \eta \text{ larger than about 5})\) or large specific fracture energy increases with the strain rate.
The Round Robin Project *IRIS 2012* requested predictions of the complete response of samples with specified nominal properties of five structural systems (a) to (e). The first three cases refer to static standard tests employed to determine material properties to be used in the response predictions of the ensuing impact problems (d) and (e).
FINAL REMARKS ON INHERENT UNCERTAINTIES

- A total of 27 qualified participants submitted 135 complex analyses, each of which demands careful consideration of material models, numerical simulation, boundary conditions, among other relevant issues, rendering the task of conducting a critical review simply overwhelming.

- Thus a final, global review has not yet been completed due to various circumstances. Nevertheless, the IRIS 2012 Proceedings constitute an extremely valuable depository of data on both Model and Phenomenological Uncertainties.
The models employed by *IRIS 2012* participants may be classified in the following groups:

1. Models based on a Continuum Mechanics approach to the material behavior of solids, such as the Finite Element Method (*FEM*) or Boundary Element Method (*BEM*) formulations. The approach constitutes the standard method of analysis of linear elastic structural systems.
(2) Models based on the representation of structural systems by a collection of discrete elements or bodies, *which cannot be subdivided*, linked by massless elements, (or simply inter-element forces), which when rupture occurs give rise to fissures or cracks, that is, to *discontinuities* in the system. These models are herein grouped within the so-called Discrete Element Methods (*DEM*).
(3) An approach derived from the numerical analysis of large groups of particles, initially applied to the study of the formation and evolution of proto-stars and of fluid flow and now extensively used in the determination of the response of solids that experience plastic flow, fracture and fragmentation, known as Smoothed Particle Hydrodynamics (SPH). The approach shares some common features with DEM, except that in the former inter-particle forces can exist between any pair of particles in the system, while in the latter they are typically restricted to *initially neighbor particles*. 
It was suggested before that the \textit{mean} load-time function for aircraft impact against target structures that suffer minor damage during the crash may be determined with small uncertainty, reflected in the proposed coefficient of variation of the peak load $CV=0.05$.

A preliminary evaluation of IRIS 2012 results led to $CV$ of the parameters defining peak structural response not smaller than 25\%, fact that should be taken into account in the assessment of numerical response predictions.
Finally, note that the uncertainty inherent in methods of analysis in group (a) (*FEM* approach) and (b) (*DEM* approach), as described above, may be expected to be smaller than the uncertainty associated to methods (c) (*SHP* approach), which are still in the stage of experimentation and consolidation.
A brief overview of analysis and design criteria of structures subjected to aircraft impact was presented, focusing attention on factors considered of relevance for NPP design. One of these factors is related to model uncertainty, *i.e.* to the degree of belief of the designer in the numerical or analytical model employed to determine the structural response. Note that uncertainty grows as we approach the limits of past experience, region in which the analyst and design engineer find themselves when assessing the effects of aircraft impact.
Finally, I wish to express my sincere thanks to BULATOM organizers for the opportunity provided by their invitation to exchange knowledge, experiences and ideas to make Nuclear Power safer and more reliable.