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UNCERTAINTIES IN AIRCRAFT IMPACT HAZARD DEFINITION FOR NUCLEAR FACILITIES

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Abstract:

Aircraft impact hazard often dictates the design of safety-critical civil structures of nuclear facilities. Overly conservative approach could result in significant cost consequences and underestimation can have safety implications. However, there are discrepancies amongst various stakeholders on how aircraft impact hazards are defined, as well as differences and uncertainties on the various parameters associated with aircraft impact hazard derivation. This paper presents the work undertaken to deterministically identify the sensitivity of various parameters related to hazard derivation. This was undertaken using quantitative analysis and took into considerations of various potentially significant parameters. The work undertaken and reported here increases our understanding of the sensitivity of some of the key parameters when undertaking aircraft impact assessments. The results of the sensitivity analyses identified that the aircraft type, mass and velocity have significant influence on the load-time functions. Other parameters, such as the friction coefficient, mass distribution and cargo modelling do not influence the hazard derivation as significantly as others. The results from the sensitivity studies can also provide the reviewer with a dataset to better understand under/over estimation. This can be undertaken by comparing the aircraft mass and impact velocity proposed by the Requesting Party / Licensee with this dataset, provided the chosen aircraft have similar configurations to the aircraft considered in the studies presented in this report.

Introduction

Together with seismic hazards, aircraft impact hazard often dictates the design of safety-critical civil structures of nuclear facilities. An overly conservative approach could result in significant cost consequences and underestimation can have safety implications. Despite its importance, research on aircraft impact has received less focus when compared to seismic hazards, partly because the work is often considered to be security-sensitive in nature; and partly because, unlike seismic, aircraft impact is restricted to highly critical nuclear infrastructures, and there is less available experience from other industries.

During the last decade, there have been advances in modelling and evaluation techniques of aircraft impact hazards. However, there are discrepancies amongst various stakeholders, such as Nuclear Licensees and Requesting Parties, and to a certain extent Regulators, on how aircraft impact hazards are defined. There are also differences and uncertainties on the various parameters associated with the hazard definition, e.g., the velocity and angle of impact.

Recognising this, Mott MacDonald was commissioned to undertake a research project on the assessment of uncertainties in the aircraft impact hazards. The aim is to improve understanding of the hazard definition and evaluation approaches for aircraft impact. This will provide understanding aligned with developments in Relevant Good Practice.

This paper provides a high-level summary of the work done to date.

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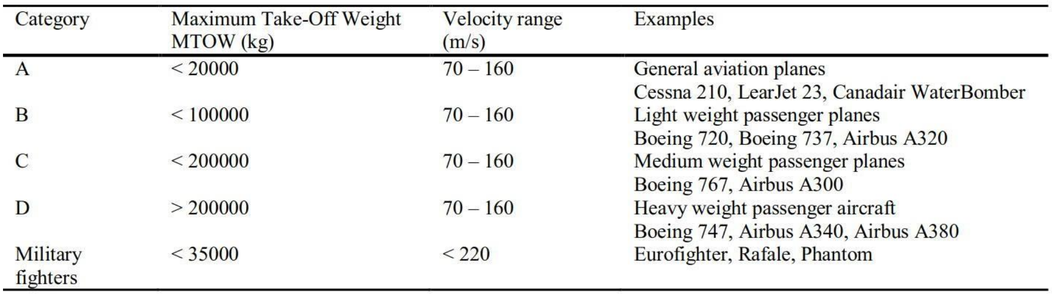
Literature Review

Compared to seismic hazards, there are limited codes, standards or guidance developed specifically for the assessment of aircraft impact. The most comprehensive and useful recent documents are as following:

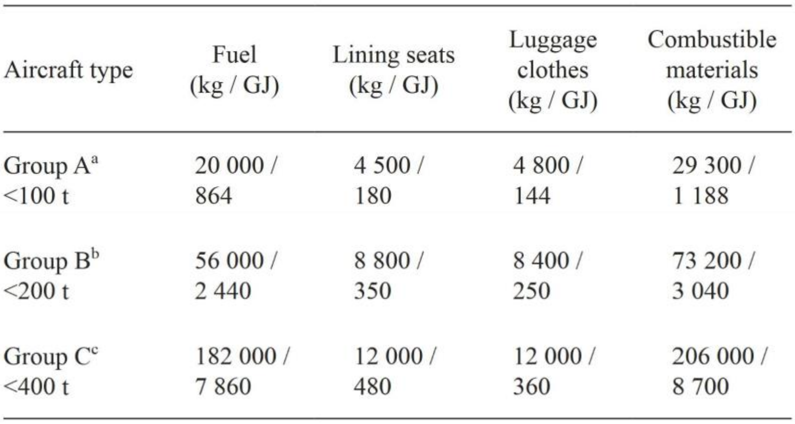
- NEI 07-13 (2011), Methodology for Performing Aircraft Impact Assessments for NewPlant Designs, Revision 8P, Nuclear Energy Institute.
- Safety Report No. 86 (2017), Safety Aspects of Nuclear Power Plants in Human InducedExternal Events: General Considerations, International Atomic Energy Agency.
- Safety Report No. 87 (2018), Safety Aspects of Nuclear Power Plants in Human InducedExternal Events: Assessment of Structures, International Atomic Energy Agency.
- Safety Report No. 88 (2017), Safety Aspects of Nuclear Power Plants in Human InducedExternal Events: Margin Assessment, International Atomic Energy Agency.
- IAEA-TECDOC-1834 (2017), Assessment of Vulnerabilities of Operating Nuclear PowerPlants to Extreme External Events, International Atomic Energy Agency.
- Office for Nuclear Regulation (2021), Technical Assessment Guide NS-TAST-GD-013 - Annex 4, Accidental Aircraft Crash Hazard, Issue 1.1, November 2021.

There are discrepancies, gaps and, sometimes, contradictory information in the documents provided for the assessment of aircraft impact. As an example, aircrafts are categorized different in various guidance documents, which could be confusing to the users. More specifically, IAEATECDOC-1834 defines aircraft categories different to IAEA Safety Report 87.



Category	Maximum Take-Off Weight MTOW (kg)	Velocity range (m/s)	Examples
A	< 20000	70 – 160	General aviation planes Cessna 210, LearJet 23, Canadair WaterBomber
B	< 100000	70 – 160	Light weight passenger planes Boeing 720, Boeing 737, Airbus A320
C	< 200000	70 – 160	Medium weight passenger planes Boeing 767, Airbus A300
D	> 200000	70 – 160	Heavy weight passenger aircraft Boeing 747, Airbus A340, Airbus A380
Military fighters	< 35000	< 220	Eurofighter, Rafale, Phantom

Table 1. Aircraft categories based on IAEA SR87



Aircraft type	Fuel (kg / GJ)	Lining seats (kg / GJ)	Luggage clothes (kg / GJ)	Combustible materials (kg / GJ)
Group A[a] <100 t	20 000 / 864	4 500 / 180	4 800 / 144	29 300 / 1 188
Group B[b] <200 t	56 000 / 2 440	8 800 / 350	8 400 / 250	73 200 / 3 040
Group C[c] <400 t	182 000 / 7 860	12 000 / 480	12 000 / 360	206 000 / 8 700

Table 2. Aircraft categories based on IAEA-TECDOC-1834

Based on the review of publicly available information, there is a lack of guidance on the nature, range, and uncertainties of the significant parameters of aircraft impact. This is understandable due to the variability of aircraft, facility designs, sites, etc., as well as the onus on applicants and licensees to justify their analyses. However, this information is also essential for the regulator to ensure consistency and proportionality in their assessment.

In summary, there are uncertainties and misalignment among various vendors, licensees, and to some extent, the regulators.

Scope and Methodology of the Research Project

This project aims to provide an improved understanding of the uncertainties associated with various impact parameters, notably:

- Aircraft types – It is commonly assumed that the most damaging impacts are caused by the largest aircrafts. However, as force is spread across the area of an impact, a large aircraft may only apply partial force to a structure compared with an impact from a smaller aircraft. Given this, it is beneficial to understand sensitivities associated with aircraft types.
- Impact parameters – Realistic impact scenarios are typically considered for beyond design basis aircraft impact scenarios, compared with design basis aircraft crash that considers conservative impact scenarios. It is important to understand the sensitivities for these realistic impact scenarios relating to the impact parameters that are used.
- Threat parameters – Fuel mass is essential for the definition of the overall impact mass of an aircraft because it represents a significant portion of the aircraft mass. However, the fuel mass must be considered with respect to the aircraft’s payload. Different approaches have been used for defining fuel mass, and it is therefore important to understand the sensitivities associated with these different approaches.

To achieve this, the project team has proceeded to deterministically identify the sensitivity of various parameters related to aircraft impact hazard derivation. This was undertaken using quantitative analysis and took into consideration the various parameters identified above. The methodology consists of:

1. Define and select aircraft type(s) to be used for the study
2. Define impact/threat parameters to be brought forward to undertake sensitivity studies
3. Define the approach for undertaking sensitivity studies and identify baselines
4. Construct and validate/verify finite element aircraft models
5. Undertake a series of analyses finite element analyses simulating the impact of the aircraftmodels onto a rigid target wall with varying parameters
6. For each analysis, a load-time function is generated by taking the reactions of the rigid wall
7. Compare results of load-time functions from analyses groups
8. Identify sensitivity-ness and findings

As a result of these steps, six aircraft models and a total of 43 explicit non-linear finite element analyses were undertaken, requiring over 2000 hours of computing runtime.

The following sections summarise the aircraft type and impact/threat parameters selections.

Aircraft Types

A range of different aircraft categories and types are required to demonstrate the sensitivities of an impact. Taking into considerations of the flight statistics, aircraft types and sizes, aircrafts with Maximum Take-Off Weight (MTOW) varying between 47 and 560 tonnes were selected, which effectively covers the whole spectrum of aircraft used in the commercial aviation. The MTOW of the aircraft is a significant parameter as it contributes to the kinetic energy delivered to the target.

The following aircraft were selected as representative for their classes and were modelled explicitly and analysed in this project:

- A representative of a typical large-scale business aviation airplanes.
- Boeing 737-800 - one of the most popular commercial airplanes with MTOW below 100 tonnes (Category A as per IAEA Safety Report No. 87).
- Boeing 767-400ER – a representative of large aircraft with MTOW below 200 tonnes (Category B as per IAEA Safety Report No. 87).
- Boeing 767-300F – one of the most popular freight airplanes in service with MTOW between 100 and 200 tonnes (Category B as per IAEA Safety Report No. 87).
- Boeing 777-300ER – Boeing 777 aircrafts are one of the world's largest twinjet commercial passenger airplanes. Boeing 777-300ER (Extended Range) is the most popular version of the 777 family (about 50% of all Boeing 777 airplanes) and is selected as a representative aircraft for long-range wide-body airliner with MTOW below 400 tonnes (Category C as per IAEA Safety Report No. 87).

- Airbus 380-800 - The Airbus 380 family are some of the largest large wide body full-length double deck commercial passenger aircrafts.

Finite element models were developed for all of the aforementioned aircrafts, with exception of the business aviation airplane which was modelled using a one-dimensional stick model (mass and stiffness distribution along the length of the aircraft), due to limited information available in the public domain. The load-time function of the business aviation airplane and its sensitivity to variation of the input parameters were studied using a simplified analytical approach (the Riera method). The load-time functions of all other aircraft were derived using finite element analysis.

	Aircraft	**MTOW, t**	**Category**	**Type**	**IAEA-TECDOC 1834 category**	**IAEA Safety Report No. 87 category**
1	Typical business aviation airplane	47	< 100 t	Business jet	B	A
2	Boeing B737-800	79	< 100 t	Passenger	B	A
3	Boeing B767-400ER	204	< 200 t	Passenger	C	B
4	Boeing B777-300ER	351	< 400 t	Passenger	D	C
5	Airbus A380-800	560	> 400 t	Passenger	D	-
6	Boeing B767-300F	187	< 200 t	Cargo	B	B

Table 3. Aircraft types and categories

Impact and Threat Parameters

As noted above, a fundamental part of the project is the sensitivity study of various input parameters defining the aircraft impact hazard. Besides different aircraft types, the following input parameters were considered in the sensitivity analyses:

- Velocity – The impact velocity is varied within a range between the landing speed and the cruising speed, with three intermediate velocities considered. The sensitivity to velocity is undertaken considering normal impact of the aircraft to the target.
- Impact angle – Sensitivity of the horizontal and vertical impact angles is undertaken considering four horizontal and four vertical angles. The angle variation sensitivity study is undertaken using only the mean velocity. The angles selected for the sensitivity analysis are illustrated in Figure 1.
- Friction coefficient – Sensitivity to the friction coefficient is considered using three values of the friction coefficient between the aircraft and the impacted surface. The friction coefficient does not influence the LTF in the case of normal impact. Therefore, the variation of the friction coefficient is undertaken considering a horizontal impact angle to the target surface. A horizontal angle of 30° has been selected based on experience as this tends to utilise frictional resistance. For angles higher than 30° impact tends to utilise less frictional resistance, whereas for lower angles it's more prone to sliding. The best estimate friction coefficient is assumed to be $\mu = 0.5$. The upper and lower bound friction coefficients can be estimated assuming a variation coefficient C_v. The upper bound friction coefficient can be calculated as $\mu_{ub} = \mu(1+C_v)$ and the lower bound friction as $\mu_{lb} = 0.5/(1+C_v)$. Assuming the C_v is equal to 1, the values of the friction coefficients used in the sensitivity analyses are provided in Table 4.
- Mass distribution –The MTOW consists of the structural mass of the aircraft, the payload and the fuel mass. Depending on the flight configuration, the distribution of the fuel mass and payload may vary, with maximum payload and fuel up to the MTOW for short distance flights, and maximum fuel and payload up to the MTOW for long distance flights. These two mass distribution configurations are considered for Boeing 767-400ER (see Figure 2). Consideration is given to the amount of fuel consumed during taxiing, take-off and reaching the target, assuming a one-hour flight. The sensitivity to mass distribution is undertaken for the normal impact scenario using the mean velocity.
- Cargo configurations – Two cargo configurations consisting of different items are considered. The first configuration includes two spare aircraft engines mounted on engine stands. The engines are assumed to be semi-deformable missiles. The engine stands are placed on the cargo deck, while the rest of the deck is loaded with general cargo. The second configuration consists of items intended to penetrate the structure placed on wooden pallets.

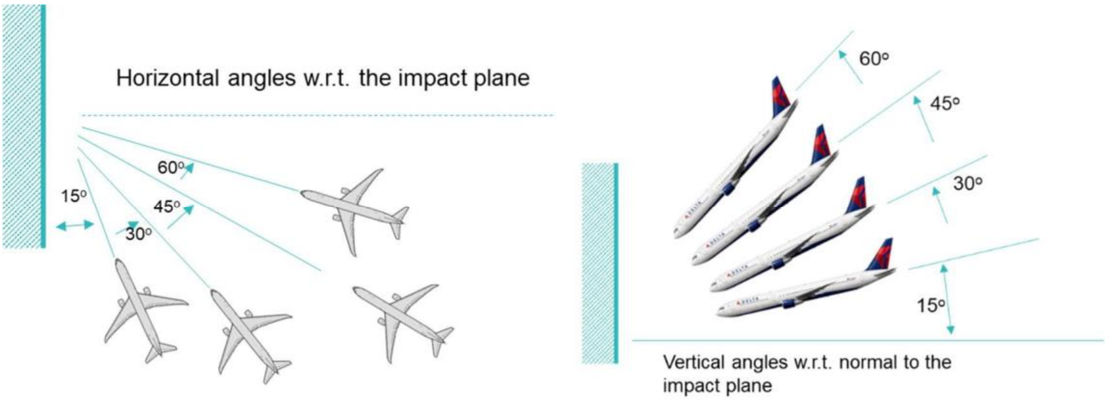


Figure 1. Horizontal and vertical impact angles (Note that the normal 90° horizontal angle is considered in the baseline analyses

Type	Friction value
Best estimate	$\mu = 0.5$
Upper bound	$\mu_{ub} = 1.0$
Lower bound	$\mu_{lb} = 0.25$

Table 4. Friction coefficients

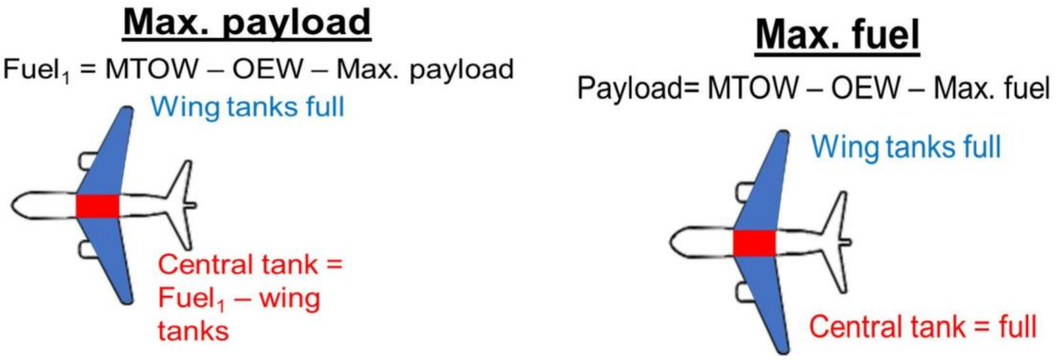


Figure 2. Mass configurations, considering (i) maximum payload, and (ii) maximum fuel

Development of Aircraft Models

Numerical modelling and analysis were undertaken using the finite element software LS-DYNA R11.1 version. The aircraft finite element (FE) models were developed using information available in the public domain:

- Manufacturer information, including published computer aided design drawings
- Reports produced by aerospace engineering consultants or experts

The business aviation airplane is the only exception. A Load-time function based on the Riera method was produced for this aircraft due to the limited information available in the public domain.

The FE models comprise shell and beam elements. The aircraft structure was modelled using shell elements, whereas stringers in the wings and fuselage were modelled using beam elements. Only structural components were modelled explicitly. These were grouped into different parts of the aircraft (e.g., wings, fuselage) and assigned appropriate material and cross-section properties. Non-structural components were not modelled explicitly but their mass was accounted for by lumping it in adjacent structural elements. The following components were not modelled explicitly:

- Aerodynamic components, such as the nose radome, fuselage fairing skin, wing and tail ailerons, flaperons, slats, spoilers, etc. However, their mass was accounted for by lumping it in adjacent structural elements.
- Rubbers parts, such as landing gear wheels, and composite parts such as the windows, were not modelled as they do not have significant contribution to the mass and stiffness of the aircraft.

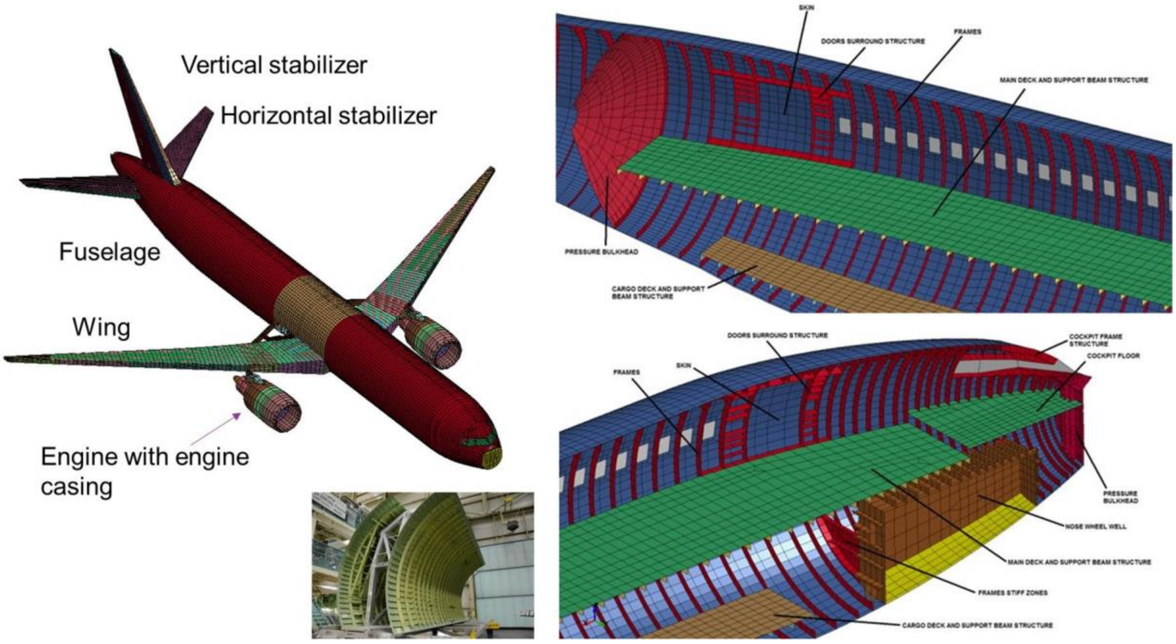


Figure 3. Finite Element Idealisation of an aircraft used for this study

Sensitivity Analysis Results

Significant amount data were generated by the project team, which are not practical to present in this paper. As an example, Figure 4 shows the normalised impulse in time for one of the aircraft categories. As the aircraft mass is constant in all analyses, the difference between the impulse patterns show in the figure are driven by the differences in initial and final aircraft velocities. Normalised data for the various aircraft types were produced for this research.

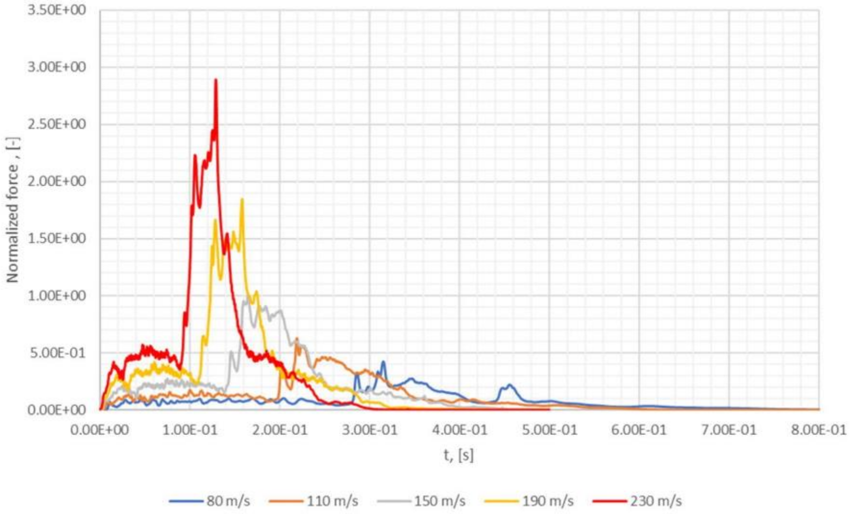


Figure 4. Load-time functions for different impact velocities of an aircraft used in this study (normal impact)

For each input parameters, a series of data point was generated. For example, for horizontal angle sensitivity analysis, four impact angles are considered: 15°, 30°, 45° and 60°. The normalized normal and tangential load-time functions are shown respectively in Figures below for all angles. It can be observed that the normal component for horizontal 60□ impact is slightly higher than normal impact force. This is due to overlap of the peak forces of the left inner and outer wings (see Figure 5).

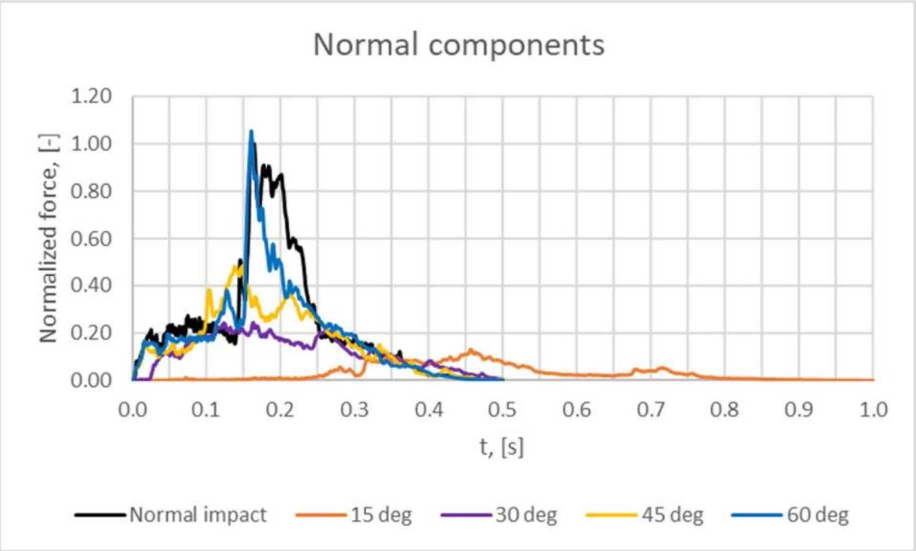
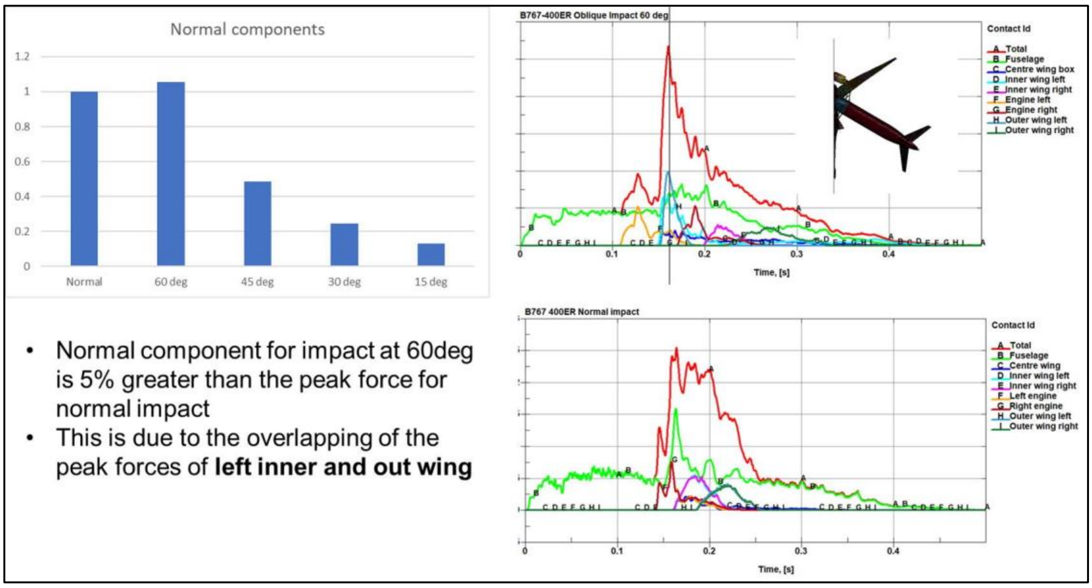


Figure 5. Normal component of load-time functions for one of the aircraft used in the study generated by varying horizontal impact angle



- Normal component for impact at 60deg is 5% greater than the peak force for normal impact
- This is due to the overlapping of the peak forces of **left inner and out wing**

Figure 6. Breakdown on a component-by-component basis for normal and 60deg impact

Similar studies have been undertaken for all of the impact parameters defined earlier, including vertical impact angle, friction coefficients, cargo configurations, impact velocities and aircraft types.

Key Findings

The following are some of the key findings of this research project:

- There is a near linear relationship between the peak force and the kinetic energy for each aircraft type. This linear relationship is established by the results of the performed FE analyses and analytical calculations provided in the relevant references.
- All analysed aircraft appear to have a very similar gradient for peak force vs kinetic energy, except for the Airbus 380-800 (which has a lower gradient). This is likely due to its smoother mass distribution along the aircraft. Therefore, all aircraft except Airbus 380-800 can be

grouped and represented by one linear relationship between the peak force and kinetic energy. This can provide the reviewer with a practical tool to quickly check the expected peak force for any pair of aircraft type/mass and impact velocity.
- Contrary to common assumption, normal impact does not provide the highest peak forces. Slightly angled horizontal impact provides higher peak forces. This is due to the overlapping of the peak forces of the left inner and outer wings with the central tank.
- Despite higher peak forces at smaller than normal impact angles, the total pressure on the target surface is similar to the pressure resulting from normal impact.
- Maximum fuel configuration is likely to be more severe than maximum payload configuration.
- The friction coefficient has little influence on the peak normal force.
- Explicit modelling of cargo introduces peaks in the load-time function, due to direct contact of the cargo mass onto a discrete area of the target. Distributed cargo (modifying selfweight of deck elements) provides a relatively smoother load-time function. However, both hard cargo configurations have identical results (in terms of peak forces in the load-time function), since the maximum peak forces are governed by the fuel and the stiffness of the wings.
- Counter-intuitively, A380-800 is not the worst case due to its wide fuselage, triple deck structure and smoother mass distribution. It provides similar peak force (and much lower pressure) when compared with other large aircraft.

Planned Future Work

Based on the results of this research work, recommendations for future work are provided. The overarching themes are:

- Additional determinist sensitivity analyses on oblique horizontal and vertical impact, and sensitivity analyses of strain erosion criteria
- Use of the Smoothed Particle Hydrodynamics method for modelling aircraft fuel and effects on the load-time function
- Sensitivity studies of vibratory in-structure response spectra
- Use of probabilistic approaches to determine a set of load-time functions for different confidence levels. This is in view of establishing a graded approach for design of new nuclear facilities and assessment of existing nuclear facilities based on the safety significance of the nuclear installation and its remaining lifetime.

Conclusions

The work undertaken and reported here increases our understanding of the sensitivity of some of the key parameters when undertaking aircraft impact assessments. The results of the sensitivity analyses identified that the aircraft type, mass and velocity have important influences on the resulting load-time function. Other parameters, such as the impact angle, friction coefficient, mass distribution and cargo modelling are not as influential on the load-time function. This suggests that for definition of load-time function more emphasis can be given to the more significant parameters, with less emphasis on other parameters.

The results from the sensitivity studies can also provide the reviewer with a dataset to better understand under/over estimation. This can be undertaken by comparing the aircraft mass and impact velocity proposed by the Requesting Parties/Licensees with this dataset, provided the chosen aircraft have similar configurations to the aircraft considered in the studies presented in this report.

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