Transactions, SMiRT-26
Berlin/Potsdam, Germany, July 10-15, 2022
Division 04

Performance-based design for airplane crash shields of nuclear buildings. Part 2: Probabilistic fragility assessment

PM. Alliard[1], J. Chataigner[2]

[1] International project director, Tractebel Engie, Lyon, France (pierre-marie.alliard@centraliens.net)
[2] Technical director, Tractebel Engie, Lyon, France (jacques.chataigner@tractebel.engie.com)

ABSTRACT

In the “Part 1: Deterministic approach by engineering charts”, a normalized load time function for commercial aircraft impact (also called Riera load function), defined as a simple function of the mass and the speed of the impacting aircraft (see Alliard 2016) was used to perform deterministic design of a reinforced concrete shield. With the help of a simplified analytical model of the target complying with RCC-CW design code and hereafter identified as “3DDL model” (3 masses with 3 non-linear springs), parametric case studies of rectangular walls and roofslabs have been run, with various span, thickness, and steel reinforcement principles. Different masses and velocities of impacting aircraft have been tested. It has finally enabled to provide useful damage level pictures as a function of the impact parameters: maximal take-off weight (100-400 tons), spent fuel mass (beginning or end of flight conditions), and velocity (100-175 m/s). The nose-down angle is fixed at realistic descent angle enabling controllability according to simulators (10-30 degrees relatively to horizontal axis). This work was motivated by the statement that there is a lack of guidelines in terms of pragmatic approach for aircraft crash shielding walls design, excepted some generic recommendations on minimal concrete thickness without relationship with the aircraft parameters of mass, velocity or angle. Our engineering charts have been developed to help designers at feasibility or basic design stage to select the most appropriate design principles, before proceeding to verification stage using advanced dynamic computational methods.

Although aircraft impact is usually considered as a beyond design situation, in the sense that elasto-plastic response is typically admitted for civil structures design as long as global safety requirements are met in terms of stability, confinement, fire and safe shut down, the design methods always remain realistic and deterministic. Yet, as reminded by Andonov (2017), a recent IAEA Safety Report (2017) on margin assessment for human-induced loads recommends the use of fragility curves to assess the structural margin for aircraft impact loads. It recommends the derivation of fragility curves based on the impact velocity as a reference parameter, but the report does not provide any guidance on the estimate of the uncertainty β.

Therefore, in the present Part 2 of our work, a tentative example of fragility analysis is developed following the same mindset of the so-called EPRI method for earthquake assessment. It enables to evaluate the robustness of the deterministic design, for an assumed set of impact conditions (mass, velocity, angle) and a required damage acceptance level, with respect to higher impact loads, considering various sources of uncertainties including approximations coming from the proposed normalized load time function and the simplified calculation method introduced for target response analysis. Uncertainty β is estimated and examples of application are discussed.

PARAMETERS AND GENERAL METHODOLOGY

The reference parameter is the impact velocity V_{ref}.

The aircraft mass is here considered as an input requirement defined by the maximal take-off weight MTOW and possibly the spent fuel mass during the flight, imposed by a safety authority but not as a probabilistic value.

The velocity V leading to failure of impacted structure is assumed to follow a log-normal distribution. The median velocity at 50% confidence $V_{0.50}$ leading to failure of the reinforced concrete shield is then defined as:

$$V_{0.50} = F \times V_{ref} \qquad (1)$$

$$F = F_C \times F_R \qquad (2)$$

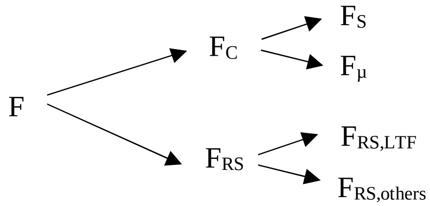


Figure 1. Decomposition of the evaluated margin factors for aircraft impact assessment

Reading of our design charts (see our twin paper Part 1), for a given mass of aircraft at the time of impact, provides the reference capacity in terms of acceptable velocity V_{ref} before impact, instead of ground acceleration for earthquake evaluation. Then, different margin factors are combined: F_s is the strength factor; F_μ is the ductility factor ; $F_{RS,\ LTF}$ and $F_{RS,others}$ are the structural response factors coming from the load time function, and other parameters respectively.

Finally, the High Confidence Low Probability of Failure velocity is V_{HCLPF} where β_u and β_r are the global logarithmic standard deviations for uncertainties and randomness:

$$V_{HCLPF} = V_{0.50}\, e^{-1,65\,(\beta u+\beta r)} \qquad (3)$$

Each parameter is evaluated in next sections.

It is remarkable that an exhaustive study was presented by Henkel (2014) to compute for a given aircraft the response related to many aleatory parameters such as the onboard mass (passengers, kerosene), the nose-down angle, the material strength, the impact velocity, etc. using complex finite element calculations: in that great report, incidence on the peak load was measured very high, up to factor three at 95% confidence compared to median case, which makes think of logarithmic standard deviation close to 0.66 on v^2 scale. However, in our own study, the onboard mass is not a probabilistic value so that lower deviation is expected.

EXAMPLE OF APPLICATION

General assumptions

Let’s consider shield building designed in compliance with EUR minimal requirements (1.30m thickness):

- Roofslab, dimensions 20m x 20m, concrete 1.30m, rebars principles 2Φ32@200 /side/direction.
- Wall, dimensions 20m x 20m, concrete 1.30m, rebars principles 2Φ32@200 /side/direction.

The nose-down angle (descent angle of the aircraft relative to horizontal axis) is fixed at 30° for the roofslab and 10° for the vertical wall. High densities of stirrups are assumed to be installed in these structural elements in order to analyze only their bending failure mode and exclude any punching cones failure. Global rebars ratio is 220kg/m^3 in raw estimate, and 250kg/m^3 after consideration of construction detailing rules such as overlapping areas.

The acceptance criterion is defined by ultimate failure (no residual margin).
The aircraft mass is an input data in the range 100-400 tons.

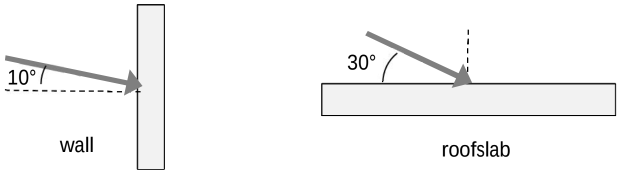


Figure 2. Angle of impact

Discussion on individual margin factors and variabilities

Capacity factor

ü Strength factor:

The deterministic engineering charts enable to evaluate the starting point of the fragility analysis V_{ref} (see Table 1) Then, a margin shall be credited to represent the difference between median and characteristic strength, for concrete and steel rebars. A typical admitted estimate is: $F_s \approx 1.15$

A typical conservative order of magnitude of the logarithmic standard deviation parameters for uncertainties in reinforced concrete structures is: $\beta_{s,u} =$ 0.15 to 0.35

It reflects target constitutive materials variabilities, including strength and execution tolerances on dimensions. These estimates come from seismic analysis (see Dolsek 2011 and EPRI 2018), which may be not relevant for aircraft studies because failure modes are obviously different. So, a more refined estimate by separation of variables is also presented hereinafter according to our feedback (see Table 2).

Concerning randomness, the following value is selected (see EPRI 2018): $\beta_{s,r} = 0.05$

Case of a 1.30 thick roof shield. Nose down angle 30°				
Beginning or End of flight	MTOW = 100T	MTOW = 200T	MTOW = 300T	MTOW = 400T
M_{impact} = MTOW	180	150	140	125
M_{impact} = 0.7MTOW	220	200	195	190

Case of a 1.30m thick vertical wall. Nose down angle 10°				
Beginning or End of flight	MTOW = 100T	MTOW = 200T	MTOW = 300T	MTOW = 400T
M_{impact} = MTOW	115	95	95	85
M_{impact} = 0.7 MTOW	175	135	135	125

Table 1. Deterministic velocity before failure V_{ref} (m/s)

ü Ductility factor

Plasticity effects are already taken into account in the analytical model for computing the target response and the deterministic engineering charts which are used to determine the starting point v_{ref}. No margin factor is therefore credited.

	Values of the deterministic analysis	$\beta_{s,u}$
Reinforcement (longitudinal)		
$A_{s,inf}$ (cm²/m)	80.4	0.089
$A_{s,sup}$ (cm²/m)	80.4	0.089
$Cover_{inf}$ (m)	0.1	0.06
$Cover_{sup}$ (m)	0.1	0.06
Reinforcement (stirrups)		
Φ (mm)	20	0.016
Spacing s_L (mm)	200	0.058
Spacing s_T (mm)	200	0.058
Target geometry		
Thickness (m)	1.3	0.019
Equ. Radius (m)	10.4	0.045
Cone angle (°)	32	0.073
Materials		
f_y (MPa)	500	0.085
f_u/f_y	1.2	0.055
E_s (MPa)	200000	0.011
$f_{cm} = f_{ck} + 8$ (MPa)	48	0.11
E_c (MPa)	35000	0.01

Table 2. Contributors to the strength logarithmic standard deviation by separation of variables. Values are derived from civil works design common practice and norms.

Response factor

- Load Time Function factor:

In seismic analyses, the margin response factors related to the input load characterization are generally the spectral shape factor, ground incoherence factor, combination of direction factor. Here, they are replaced by a probabilistic factor attached to the Riera load time function for aircraft impact. Comparison of our normalized model with available calculated load time functions (see Alliard 2016 and twin paper Part 1) revealed that our model introduces the following margin and uncertainties: $F_{RS,LTF} = 1.07$

Great dispersion between β_{LTF} as computed with conservative method or numeric simulation method comes from the shape of the peak ramp-up (triangular/rectangular pulse front) and the complex behaviour of the model representing the target itself. Consequently, we carried out refined sensitivity analyses using Latin Hypercube Sampling technique based on 40 random runs to directly determine $\beta_{LTF,u}$, all other parameters being assumed fixed. The exercise was repeated for two different scenarios of given couple {aircraft mass; target slab}. It was observed that the ramp-up shape does not affect significantly the bending response, because the roofslab fundamental period of vibration remains high compared to the characteristic time of the impulse. This is more impacting for the concrete cone punching, which was not studied in present example due to large quantity of stirrups. The global variability of the calculated reference velocity of failure, due to single normalized load time function uncertainties, was calculated as $\beta_{LTF,u} = 0.36$ (on v² scale), which is much less than the value conservatively computed through quadratic sum of elementary variabilities and seems much more realistic.

Moreover, we must have in mind that even if in our method the mass is an input data imposed by a Regulator, parameter M0 will always be submitted to small variations (number of passengers, freight weight, actual amount of fuel). In our model, simulations have shown that ~5% error on mass assumption can propagate a randomness variability of failure speed equal to $\beta_{LTF,r} = 0.072$ (on v² scale), which is typically 20% of the uncertainty variability.

	$\beta_{LTF,u}$
Peak load of the LTF	0.21
Peak time of the LTF	0.22
Peak ramp-up duration of the LTF	0.65
Global LTF variability (Conservative computation = square root of quadratic sum of βi)	0.72
Global LTF variability (Optimized computation = LHS simulations of v_{ref}^2)	0.36

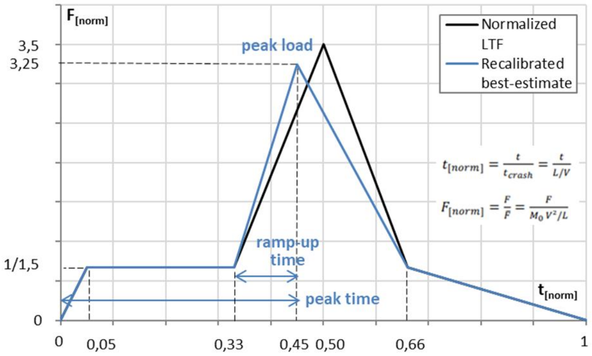


Figure 3. Contributors to the load time function logarithmic standard deviation

ü Other response factors:

It is assumed that the simplified analytical model, which was used to compute the strength analysis and the engineering charts, provides best estimate response when setting parameters at the values prescribed in Afcen RCC-CW 2019 code (ex: damping, materials non-linear laws, etc.). Indeed, our feedback from previous projects has shown that it is actually even slightly conservative compared to fast dynamic finite element calculations. No margin is here credited to remain safe: $F_{RS,Others} = F_{RS,Modeling} = 1.0$

The variability is affected by different sources in the computation process of the structural response. Two main contributors can be highlighted:

- Modeling details and fidelity: this is related to the refinement of the structural model. It can affect the frequency, mode shape and finally the stress analysis in response. In first estimate, we refer by analogy to the values given by RCC-CW code for earthquake analysis. $\beta_{r,RS,Mode\ shape} = 0$ and $\beta_{u,RS,Mode\ shape} = 0.05$ to 0.15. The most conservative is selected when the structural model is not detailed enough, such as analytical model (no 3D finite element model). Values approx. 0.10 to 0.15 are also mentioned in EPRI guidelines. It is true it is more relevant for seismic shear walls than for bending slab in out-of-plane response.
- Damping: our simplified model assumes 2% for the punching concrete cone, 7% for the bending slab and the surrounding structure in accordance with RCC-CW prescriptions for load drops and missile impacts. Yet, damping can actually change through the course of the impact as the structure reaches yield and cracking, driving down the frequency and up the effective damping. Nevertheless, most of the energy dissipation in large aircraft impact analysis comes from the great non-linear bending response of the reinforced concrete target. It was confirmed by testing other assumptions that variability coming from damping is insignificant (<0.01).

Computation of the global margin factor and variability

The global margin factor is $F = F_c \times F_{RS,\ LTF} \times F_{RS,modeling} = 1.15 \times 1.07 \times 1 = 1.23$
Two approaches have been tested to compute the global variabilities. First methodology is the quadratic summation. However, this approach is not really relevant when the response is governed by multiple parameters in complex formulations other than simple multiplications and using non-linear models. The second approach is the Latin Hypercube Sampling technique. A set of 40 random simulations was generated, applying individual logarithmic standard deviation to all variable parameters described in previous pages (input load time function, target materials and geometry). The exercise was repeated for two different scenarios of given {aircraft mass ; target slab design}. It was observed that the effective variability of the failure velocity v^2_{ref} is much optimized. Moreover, realistic individual contribution of the strength uncertainty (materials, geometry) to the global uncertainty can be estimated as $(0.39^2-0.36^2)^{0.5} = 0.15$ instead of the previously assumed value 0.25. The main contributor is the LTF peak load variability.

	Uncertainty		Randomness
	Quadratic sum	LHS method	Quadratic sum
Input Load Time Fonction: $\beta_{RS,LTF}$	0.72	0.36 (40 runs of 100T aircraft) 0.36 (40 runs of 200T aircraft)	0.072
Strength β_s	0.25	See individual values in Table 3	0.05
$\beta_{global\ excepted\ RS\ modeling}$ $= (\beta_{RS,LTF}^2 + \beta_s^2)^{0.5}$	0.76	0.39 (40 runs of 100T aircraft) 0.39 (40 runs of 200T aircraft)	0.10
Structural dynamic modeling of the slab: $\beta_{RS,modeling}$	0.15	0.15	-
Global variability: $\beta_{u,global}$; $\beta_{r,global}$	0.77	0.42	0.10

Table 3. Global logarithmic standard deviation (on a demand axis expressed in v^2)

Presentation of final results

The optimized global logarithmic variabilities obtained using LHS sampling have been kept for use in following final paragraph. The logarithmic standard deviation corresponds to the spreading of the fragility curves as a function of the demand. For earthquake analysis, the demand is proportional to the acceleration. But, for aircraft impact, the demand is proportional to MV^2 (kinetic energy and peak load as well). So, in order to plot the final fragility curves as function of the velocity v (x-axis) instead of v^2, a scaling correction is applied to the margin factors ($F^{0.5}$) and to the variability factors (½ β).

$F = 1.22^{0.5} = 1.11$; $\beta_{u,global} = ½ \times 0.42 = 0.21$; $\beta_{r,global} = ½ \times 0.10 = 0.05$
(corrected parameters for velocity scaling of x-axis)

This example shows that the HCLPF velocity for flexural failure mode of the impacted wall or roofslab can be in the same order of magnitude as the landing speed, and is 35% lower than the median value (see Tables 1 and 4). Figures 5 and 6 plot the resulting fragility curves for the100T and 200T aircrafts.

Then, in order to determine the probability of "success" of intentional hit combined with ultimate failure of the target, the best estimate fragility curve is crossed with a risk curve (see Figures 5 to 7). For an intentional act with an experienced pilot, it is considered that probability to hit the target structure is 0.5 (50 % probability of success) at 175 m/s and 1.0 (100 % probability of success) at 100m/s (see Henkel 2014 and Maly 2015).

Case of a 1.30 thick roof shield. Nose down angle 30°				
Beginning or End of flight	MTOW = 100T	MTOW = 200T	MTOW = 300T	MTOW = 400T
M_{impact} = MTOW	130	109	101	91
M_{impact} = 0.7 MTOW	159	145	141	138

Case of a 1.30m thick vertical wall. Nose down angle 10°				
Beginning or End of flight	MTOW = 100T	MTOW = 200T	MTOW = 300T	MTOW = 400T
M_{impact} = MTOW	83	69	69	62
M_{impact} = 0.7 MTOW	127	98	98	91

Table 4. High Confidence Low Probability of Failure velocity of aircraft V_{HCLPF} (m/s).

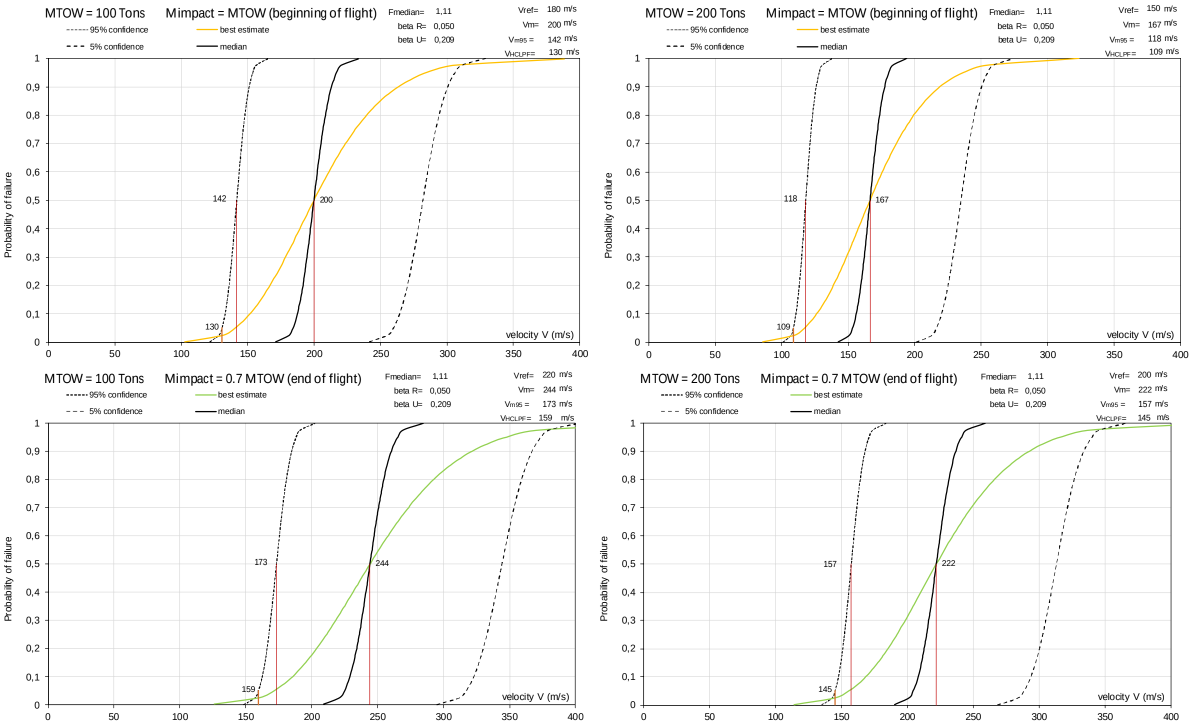


Figure 4. Example of fragility curves. For a given design 1.30m thick.
Case of a roof shield. MTOW = 100-200T. Nose down angle 30°.

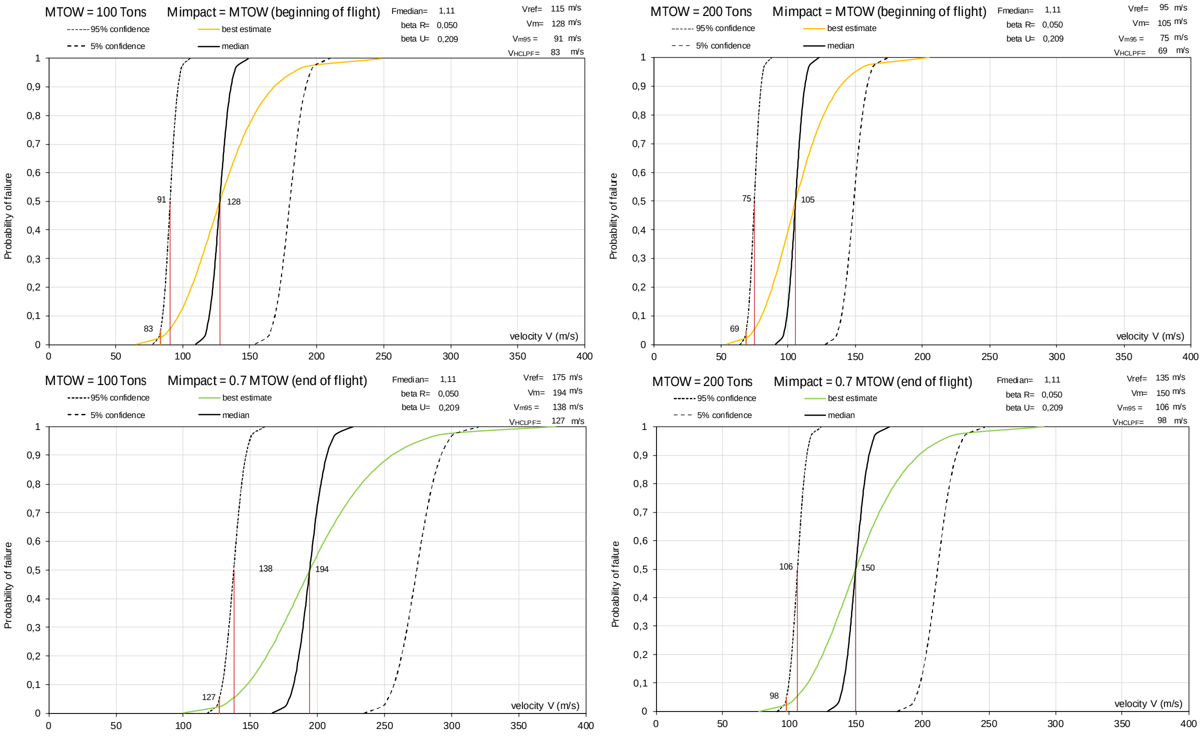
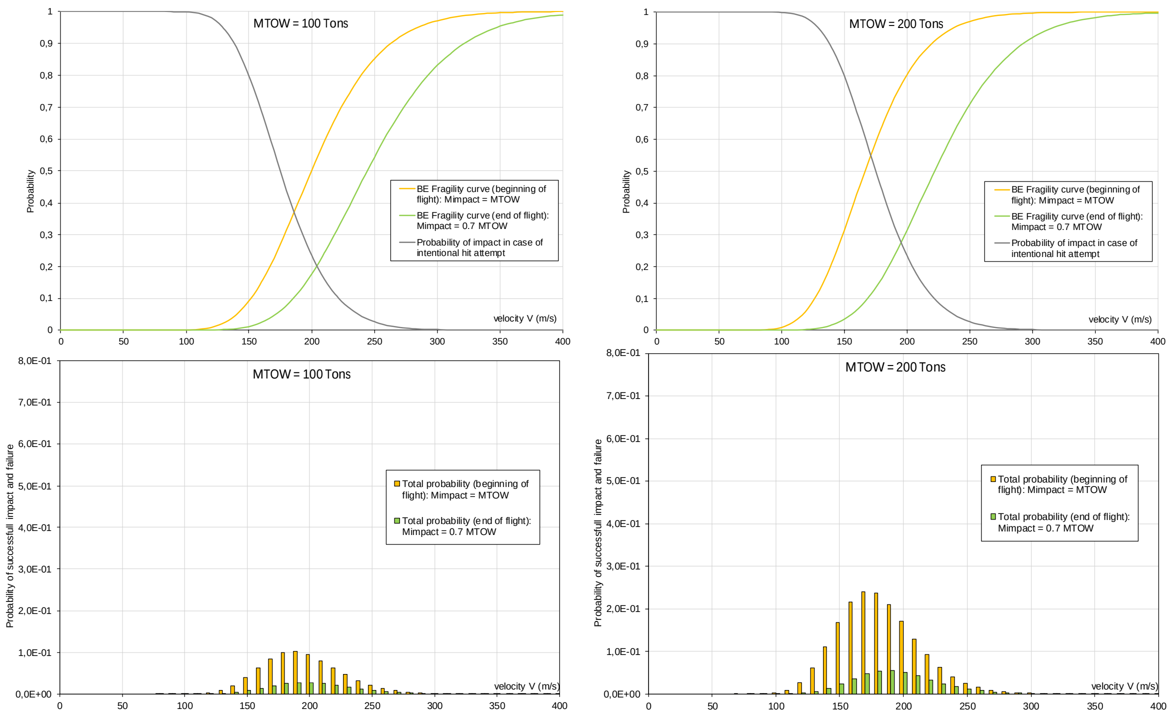
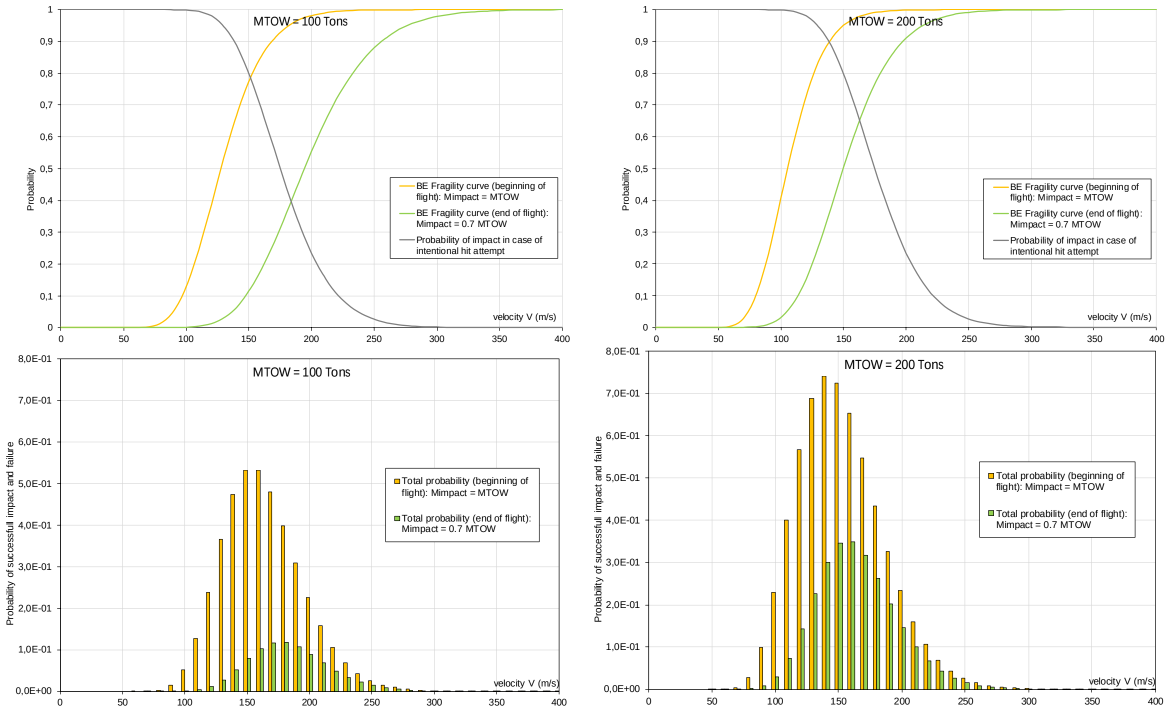


Figure 5. Example of fragility curves. For a given design 1.30m thick.
Case of a vertical wall. MTOW = 100-200T. Nose down angle 10°.



Velocity that maximizes the cumulated probability of successful strike 100-200 Tons together with ultimate failure of the shield is 170-190m/s

Figure 6. Example of intentional APC probability calculation for a given design 1.30m. Case of a roof shield. MTOW = 100-200T. Nose down angle 30°.



Velocity that maximizes the cumulated probability of successful strike 100-200 Tons together with ultimate failure of the shield is 140-160m/s

Figure 7. Example of intentional APC probability calculation for a given design 1.30m. Case of a vertical wall. MTOW = 100-200T. Nose down angle 10°.

CONCLUSION

Our first paper (Alliard 2016) had proposed a standard load time function based on the observation of available curves in the literary and normalized assumptions for the aircraft characteristics.

Then, in the twin paper "Part 1: Deterministic approach" attached to present paper, some engineering damage charts have been developed applying this load time function to many configurations of aircraft mass, velocity, target structure geometry and design principles. It is now possible to use these charts as efficient tool in preliminary design of a new build project, and inversely for diagnosis of an existing one.

In that second paper, we focused on the weight of uncertainties related to parameters to compute the proposed failure speed values. Indeed, the deterministic design is based on a standard load time function, combined with a simplified dynamic structural model, which could appear obviously questionable. By analogy with seismic margin assessment methodologies, one can plot fragility curves as a function of the aircraft velocity to appreciate the robustness of the structural design with respect to such extreme external hazards. The aircraft mass and descent angle are still assumed fixed by regulatory requirement and realistic considerations of controllability. Conclusions that may be drawn from this probabilistic analysis are then:

- The variability of the demand alone (namely the Riera load time function) is estimated $\beta_u = 0.36$ and $\beta_r = 0.072$ on a load or energy scale (mv^2 scale), because of uncertainties in the modeling of the aircraft and randomness. Then, the global variability, including uncertainties to the load time function as well as the target parameters (construction execution tolerances, material characteristics, modeling simplicity, etc.) is estimated by a series of random tests using Latin Hypercube Sampling technique. Results are more accurate than by the simple quadratic summation, which would have been not appropriate for non-linear response ($\beta_{u,global} = 0.42$ and $\beta_{r,global} = 0.10$).

- An example is dealt for a 1.30m thick shield building in compliance with in EUR prescriptions, and aircraft descent angle 10-30° to the horizontal direction (see Figures 5 and 6). The critical part is definitely the vertical walls which are submitted to almost perpendicular impact. The High Confidence Low Probability of Failure velocity is in the range 62-83m/s right after take-off for aircrafts capacity 100-400t, or 91-127m/s in end-of flight spent fuel mass conditions. There is no margin in comparison with the landing speed, namely a speed which offers good controllability to hit the target with high probability of success. This is lower than the recommended performance criteria $v_{HCLPF} \geq 135$m/s (see IAEA 2017) excepted for short distance aircraft hitting the roofslab without kerosene mass. Such poor performance can be explained by the fact that a deterministic design, typically made for median velocity ~150m/s already takes benefits from the elasto-plastic capacity of reinforced concrete structures, thus letting few residual margin to balance with uncertainties and randomness effects in probabilistic analyses.

- The velocity that maximizes the cumulated probability of successful strike together with ultimate failure of the shield is estimated 150-160m/s for aircraft 100-200t, all parts of building considered (namely average of external wall or roofslab studies. See Figure 4). The maximal probability is not neglectable and to be multiplicated by the probability of occurrence of such crash, whatever intentional or accidental (information which is not evaluated by the authors).
  The cumulated risk (integration of the area) is increased by factor 3 when the intentional crash occurs at beginning of flight instead of end of flight, because of the kerosene mass (see Figure 4).

As a conclusion, it can be stated that an EUR compliant shield building may have questionable robustness with respect to the largest commercial aircrafts when a certain level of uncertainty is considered in the analyses. EUR prescriptions sound appropriate only for short distance commercials at landing speed (typically A320 class). This class represents 37% of the relative frequency of occurrence in the worldwide airplane traffic. Larger concrete thickness could be recommended to cover a wider range of situations.

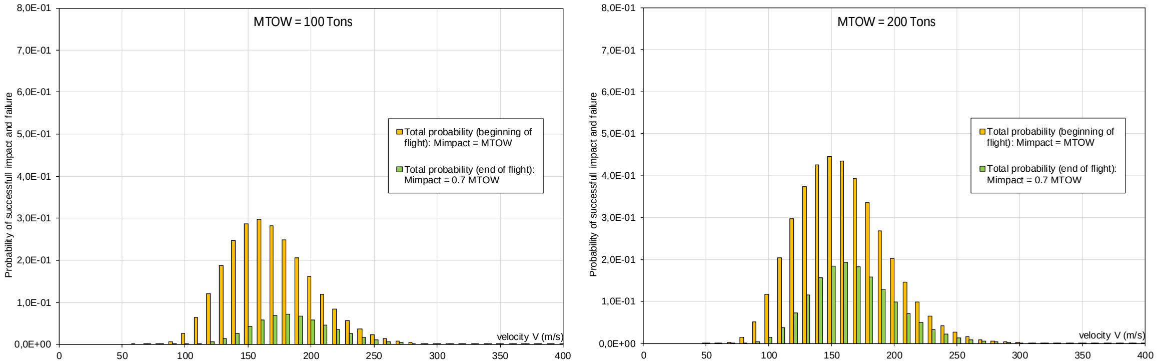


Figure 8. Example of intentional APC probability calculation for a given design 1.30m. Average wall or roofslab. MTOW = 100-200T.

REFERENCES

Alliard PM., and Chataigner J. (2016). "Impact load curve for commercial aircrafts: a normalized model", *TINCE Conference, September 5-9, 2016, Paris, France.*

Andonov, A. et al. (2017). "Performance-based design of reactor buildings for aircraft impact loads", *Transactions SMIRT24, Bexco Busan, Korea – August 20-25, 2017 Division III*

AFCEN RCC-CW (2019), *Rules for design and construction of PWR Nuclear civil works*, Afcen.

Dolsek M. (2011). "Seismic Risk Assessment of Reinforced Concrete Frame with Consideration of Aleatory and Epistemic Uncertainty", *Dec 2011, Procedia Engineering, 14:982-988*

EPRI, "Seismic Fragility and Seismic Margin Guidance for Seismic Probabilistic Risk Assessment", *Electric Power Research Institute, 3002012994, Final Report, Sept 2018.*

EUR. European Utility Requirements For LWR Nuclear Power Plants, Rev. C, Section 2.1.5.3.4

Henkel, F.O and Kostov, M. (2014). "Risk Protec CI – Risk Assessment and Development of Protection Capacity for Critical Infrastructures due to Aircraft Attack", *Dissemination Book, Sofia 2014.*

IAEA Safety Report No. 88 "Safety Aspects of Nuclear Power Plants in Human Induced External Events: Margin Assessment", *International Atomic Energy Agency (IAEA, 2017)*

Maly, J., and Vacek J. (2015). "Design parameters for selected external hazards – large aircraft impact and wind generated missiles", *Post-SMIRT23, Istanbul, Turkey – October 21-23, 2015.*