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Performance-based design for airplane crash shields of nuclear buildings. Part 1: Deterministic approach by engineering charts

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ABSTRACT

A normalized load time function for commercial aircraft impact (also called Riera load function) was proposed by Alliard (2016), as a simple function of the mass and the speed of the impacting aircraft. This standard model was motivated by the need to get an efficient engineering formulation for use at preliminary design stage. It was based on:

(i) inventory of large range of commercial aircrafts geometrical characteristics, and assumption of generic relative mass distribution
(ii) validity domain: buckling force of fuselage not significant compared to inertial forces, checked when $v > 150$ m/s and $M_0 > 100$ tons.
(iii) constant velocity during the impact, leading to simple formulation of the duration t_{crash} and conservation of impulse momentum $M_0.v$ (integration of the load time function F(t))
(iv) possibility to make distinction between impact occurring at the maximal take-off weight (conservative case), or impact at end of flight when fuel gauge has significantly decreased.
(v) observation of various available load time functions taken from the scientific literary in the past years, by means of different methods from simplified to advanced dynamics calculations, and for various sizes of commercial airplanes, in order to propose a best estimate function F(t).

In the present paper, the comparative database has been enriched by interpreting additional information from Tieping (2019), Blandford (2009), Henkel (2014), Kostov (2013), Korotkov (2016), Kultsev (2013), Forasassi (2010) and IAEA (2017) for different aircrafts and assumptions of fuel payload. The case of cargo aircraft is not dealt.

Furthermore, this model has been used to run parametric case studies of rectangular walls and roofslabs, with various span, thickness and rebars principles. Different masses of impact and velocities have been tested. It finally enables 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. This work was motivated by the statement that there is a lack of guidelines in terms of accurate design principles, excepted generic recommendations on minimal concrete thickness without relationship with the aircraft parameters of mass, velocity or angle (see EUR). Engineering charts are developed to help designers at feasibility or basic design stage to select the most appropriate design principles, before going to verification stage using advanced dynamic computational methods.

Based on these sensitive test analyses, the parameters of the pseudo-static method are also proposed in terms of dynamic load factor and plasticity reduction factor, following the same mindset as for general aviation design methods. Application examples are developed to illustrate both approaches.

REMIND OF THE MODEL AND ENRICHMENT OF THE COMPARATIVE DATABASE

The normalized load time function, fully described in Alliard (2016) is reminded here below (Figure 1). With account of these more recent additional data, the normalized model appears still convincing. It was remarked by other experts in the past that the triangular shape we selected may not be the most appropriate to represent the peak induced by the wings. However, that shape remains actually in good correlation with some of the available calculated load time functions (Figures 2 and 3). Moreover, in comparison with the incidence of peak amplitude, the impact of the shape on design verifications is limited according to our feedback, because the load ramp-up is very fast.

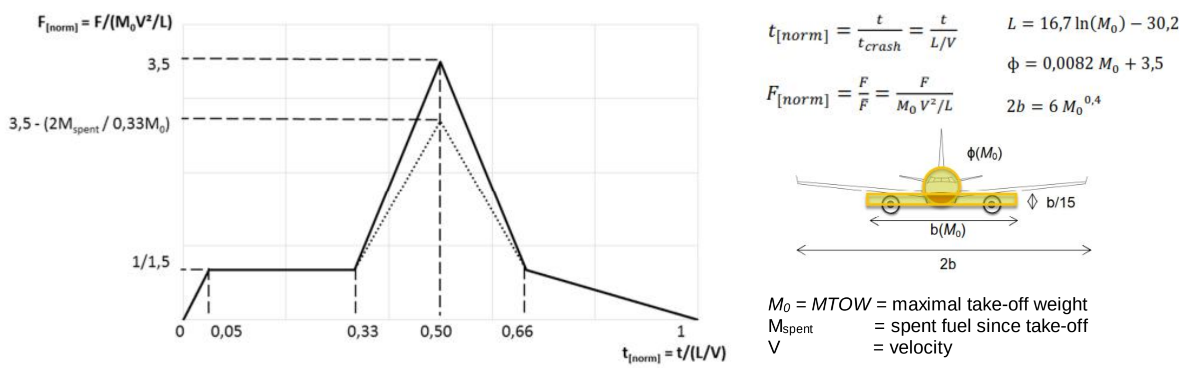


Figure 1. Normalized model

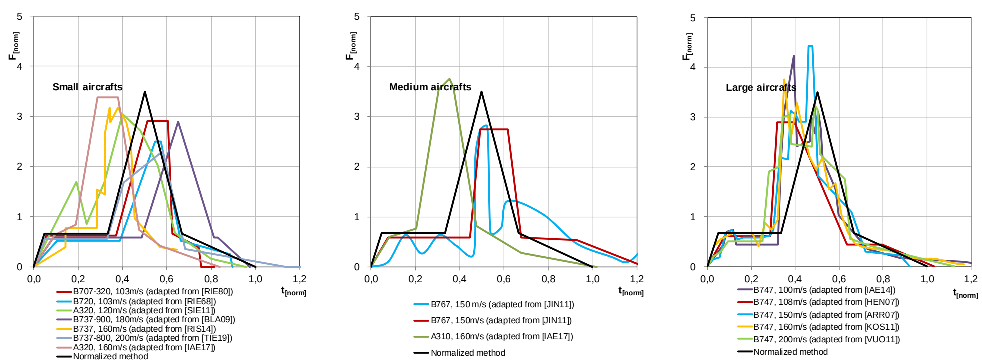


Figure 2. Comparison of available load time functions with the normalized method (full kerosene tanks gauge)

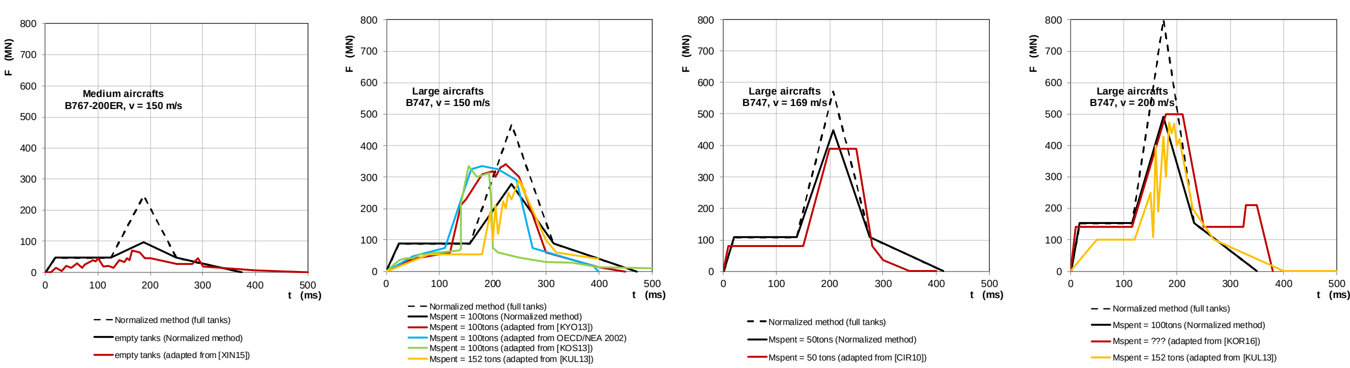


Figure 3. Comparison of available load time functions with the normalized method (low kerosene tanks gauge at end of flight)

PARAMETRIC STUDY FOR DESIGN BY ENGINEERING CHARTS

In that paper, the resistance of a flat rectangular roof slab or a vertical wall to aircraft impact is analyzed with account of a wide set of assumptions:

- 3 assumptions of span 20m x 20m, 30m x 30m, 40m x 40m
- 5 assumptions of design (concrete thickness, steel rebars principles)

Cylindrical and spherical geometries are not dealt and could be studied in some other future papers.

	Concrete f_{ck} = 40 MPa	Rebars f_y = 500 MPa		Rebars Density (kg/m3)	
	Thickness	Longitudinal per face per direction	Stirrups	Raw value	Corrected (*)
Design #1	1.20m	2 layers Φ32 /200mm	Φ14 /200x400mm²	230 kg/m³	260 kg/m³
Design #2	1.50m	2 layers Φ32 /200mm	Φ14 /200x400mm²	190 kg/m³	210 kg/m³
Design #3	1.80m	2 layers Φ32 /200mm	Φ16 /200x400mm²	165 kg/m³	185 kg/m³
Design #4	1.80m	2 layers Φ40 /200mm	Φ16 /200x400mm²	240 kg/m³	270 kg/m³
Design #5	1.80m	3 layers Φ40 /200mm	Φ20 /200x400mm²	350 kg/m³	400 kg/m³

(*) including detailing rules, overlapping areas, ...

Table 1: Tested design configurations for reinforced concrete shielding walls and roof slabs

The commercial aircraft parameters are tested in various scenarios:

- 4 assumptions of maximal theoretical take-off mass (MTOW = 100 to 400 T)
- 2 assumptions of mass before impact, from beginning (M_{impact} = MTOW) to end of flight (M_{impact} = 0.7 MTOW), to reflect low/high bound assumptions for kerosene consumption
- 4 assumptions of impact velocity (V = 100 to 175 m/s)

The calculations are conservative when the load time function is used out of its validity domain, namely for the smaller commercial aircrafts when the velocity is close to the landing speed. The aircraft structure should be actually not completely destroyed in such conditions.

Realistic assumption of the nose-down angle (descent angle) is in the range 10°-30° for a large aircraft, in accordance with recent studies conclusions, which are based on theoretical maximum operating conditions ensuring maneuverability an also on intentional hit simulations (see Henkel 2014, and Maly 2015). Therefore, the most conservative scenarios will be considered as follows:

- 10° when impacting a vertical target wall
- 30° when impacting a flat roof slab.

Concerning velocity, it is known that the lowest value is given by landing speed of 70-100 m/s. The upper value depends on the conditions to ensure controllability close to the ground as well as the piloting skills. Flight simulator tests on nuclear power plants demonstrated that there could be actually significant probability of matching the target at 175-180 m/s for an experienced pilot (see Henkel 2014, and Maly 2015). According to 9/11 Commission Report and Wierzbicki report, the speed of the aircrafts was estimated 192-210 m/s for North Tower, 220-264 m/s for South Tower and 237 m/s for the Pentagon. More recently in 2015, intentional crash in the French Alpes was recorded at 180 m/s (see BEA report). In case of accidental crash, the speed is likely to be closer to terminal speed of falling objects. In 1986, the space shuttle Challenger exploded in mid-air and plunged into the ocean at 80 m/s according to MIT report (see Wierzbicki report).

The methodology which is followed for reinforced concrete verifications in the parametric analyses is described in the French nuclear design code RCC-CW and Iter code I-SDCB. The charts in Appendices represent the resulting damage level in each configuration. First version of that method was named in the past "CEB method", and is also mentioned in IAEA safety report 2017. Feedback of various projects has shown that this simplified analytical model is an efficient tool to make preliminary design verification, iterative tests and the results have been observed quite reliable compared to fast dynamic finite element calculations. The model enables to deal with bending and shear cone failure modes which are coupled. Yielding of stirrups affects the response in the longitudinal rebars and inversely.

3 masses:

local mass M3 of the punching cone under the effect of the impact,
local mass M2 of the slab which is yielded in bending,
global mass M1 which represents the surrounding structure.

3 springs:

elasto-plastic spring R3 represents the punching phenomenon with the contribution of the tensile strength of concrete, the stirrups which are elongated until rupture and the bending reinforcement which develops large deformations,
elasto-plastic spring R2 represents the elasto-plastic bending of the slab,
elastic spring R1 represents the surrounding structure.

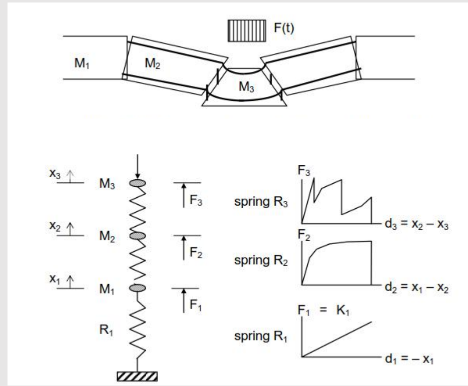


Figure 4. Analytical model of a reinforced concrete shield submitted to aircraft impact (see Afcen RCC-CW 2019 and Iter-SDCB 2012)

DISCUSSION ON STRUCTURAL DESIGN CRITERIA

IAEA performance objectives

As reminded by Andonov (2017), some performance objectives were defined by IAEA (2014):

- Design Basis External Event (DBEE)
  - • Containment / Confinement (C): required.
  - • Safe Shut Down (SD): required, multiple success paths.
  - • Decay Heat Removal (DHR): required, multiple success paths.
  - • Civil Structure: essentially elastic response

  Assessment of structural safety is based on conservative criteria.
- Design Extended External Event 1 (DEE 1)

  The following safety functions are required, IAEA (2017a):
  - • Containment / Confinement (C): required.
  - • Safe Shut-Down (SD): required, 2 success paths.
  - • Decay Heat Removal (DHR): required, 2 success paths for DEC-1

  Assessment of structural safety is based on a best estimate approach.
- Design Extended External Event 2 (DEE 2)

  The following safety functions are required, IAEA (2017a):
  - • Containment / Confinement (C): not required.
  - • Safe Shut-Down (SD): required, 1 success path.
  - • Decay Heat Removal (DHR): required, 1 success path

  Assessment of structural safety is based on a best estimate approach.

Proposal of a performance index in civil engineering language

There is a consensus in the international regulatory domain that large commercial aircraft impact belongs to beyond design event. However, in some projects conciliation of the safety criteria in terms of verification criteria for the structural engineer is not always easy task. It is here proposed to define a damage indicator expressed in percentage, the maximum damage 100% being equivalent to the performance objective DEE1 (see Table 2 hereinafter). To reach that limitation step by step, the concept of limit states can be used following the same mindset as for seismic design. However, it is remarkable that for beyond design, IAEA and US codes considers the best estimate material strengths, whereas in airplane crash sections of the French design codes, the characteristic values (95% percentile) are still used, which means that a residual margin is kept and this may sound actually inconsistent with the beyond design classification.

Our Damage index for longitudinal rebars $= \mu / \mu_{ult} = \delta / \delta_{ult}$ Where $\mu = \delta / \delta_{elast}$	**Analogy with ASCE43-05 Limit States for seismic design**	**Analogy with IAEA performance objectives, partially based on NEI 07-13**	**Analogy with Afcen RCC-CW 2019 requirements**	**Analogy with Iter-SDCB 2012 requirements**
Small	LS-D (Yield)	DBEE $\varepsilon_c = 0.35\%$ $\varepsilon_s = 1\%$	Elastic $\sigma_c = 0.4\ f_{ck}$ $\varepsilon_c = 0.28\%$ $\varepsilon_s = \varepsilon_{yk}$	
25%	LS-C			
50%	LS-B			Ultimate Limit State $\varepsilon_c = 0.5\%$ $\varepsilon_s = 0.5\varepsilon_{uk} = 2.5\%$ $\theta_{lim} =$ Min(0.025 ; 0.005/x/d) ≈ 1.5°
75%	LS-A		High cracking $\sigma_c = f_{ck}$ $\varepsilon_c = 0.35\%$ $\varepsilon_s = 0.9\ \varepsilon_{uk}$	
100% (failure) δ_{ult} determined with RCC-CW materials criteria	Ultimate capacity	DEE1 Median strength $\varepsilon_c = 0.5\%$ $\varepsilon_s = 5\%$ $\theta_{lim} = 4°$	Important damage $\sigma_c = 1.2\ f_{ck}$ $\varepsilon_c = 0.5\%$ $\varepsilon_s = \varepsilon_{uk}$ $\theta_{lim} =$ Min(ε_s ; ε_c/x/d) ≈ 3°	
		DEE2 Median strength No strain limit $\theta_{lim} = 6°$		

Our Damage index for shear stirrups	**Analogy with IAEA performance objectives, partially based on NEI 07-13**	**Analogy with Afcen RCC-CW 2019 requirements**	**Analogy with Iter-SDCB 2012 requirements**
Elastic	DBEE	Elastic	
Stirrups failure	DEE1 Confinement à interpreted as no concrete transversal cracks requirement (if no steel liner)		Ultimate Limit State
Concrete cone stopped by longitudinal rebars filet	DEE2 Loss of confinement à interpreted as possible kerosene intrusion	High cracking Important damage	Ultimate Limit State with loss of confinement

Note that the safety criteria of a specific project are highly dependent on the safety analysis (function of the building ; safety components behind the shield ; presence of steel liner at inner side can lead to tensile strain requirements at inner side ; fire intrusion acceptance and management strategy ; etc.).

Table 2: Definition of the damage index for bending and shear.
Conciliation with IAEA performance objectives and other design codes for airplane impact loads.

DESIGN BY PSEUDO-STATIC METHOD

The pseudo-static method is commonly used to design reinforced concrete shields for general aviation impact. The question could be how to adapt it for the large commercial aircraft. The force is defined by:

$$F_{pseudo\text{-}stat} = DLF \,.\, F_{max} \,.\, \cos(\theta) \,/\, R_{\mu} \qquad (1)$$

where F_{max} is the peak of the load time function. R_{μ} is the reduction factor for plasticity effects. The dynamic load factor (DLF) was evaluated for target frequencies < 20 Hz, which covers a large range of geometrical configurations for slabs and walls. The angle relative to the normal direction to the target is noted θ.

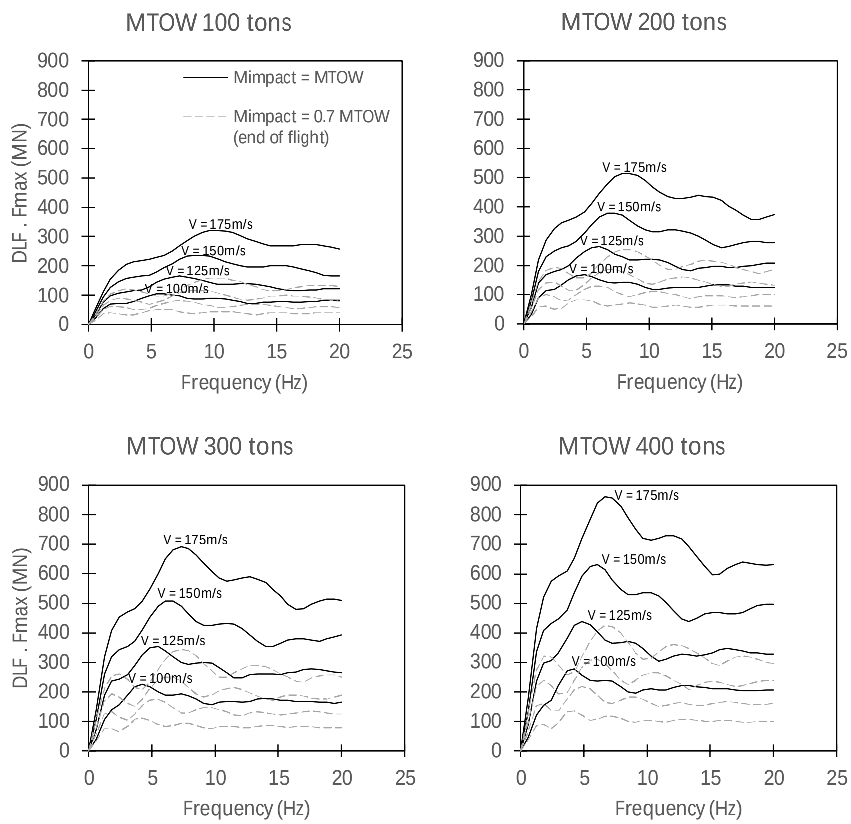


Figure 5. Dynamic load DLF. F_{max} (normal impact: $\theta = 0$; concrete damping 7%)

In our simulations, it was often observed that the case of shield dimensions 30m x 30m results in the highest damage level, whereas cases 20m x 20m and 40m x 40m are similar. Reason comes from the eigen frequency of the impacted element which is often close to the peak of the DLF function (for the cases tested here).

It is also remarkable that when end-of flight conditions are assumed (30% spent mass due to kerosene consumption), the dynamic force is actually divided by factor 2 in our model. This comes from the triangular shape of the normalized load time function, whose peak is lower and smoothed in that case as observed onto the available calculated curves (see Figure 3).

Regarding the reduction factor, one can find in the literary some usual formulations, but these estimates are actually highly dependent on many parameters such as the frequency. Miranda (1994) presented various models for seismic conditions. As the similarity of the level of plastic deformations attained by structures in seismic conditions (rather long duration of seismic loads, about 10 s or 15 s) compared to those observed in aircraft crash situation (short duration) is questionable, we propose in the present paper an evaluation specifically for airplane crash loads on rectangular fixed-end shields. The reduction factor for bending plasticity was calculated in each case of the previous parametric study, as the ratio between the maximal dynamic force and the yielding force. The formulation $R_\mu = (2\mu-1)^{1/n}$ was verified, with n = 2 to 4, respectively for large span to small span shields. Then, relationships between damage levels, reduction factors and the limit states have been plotted.

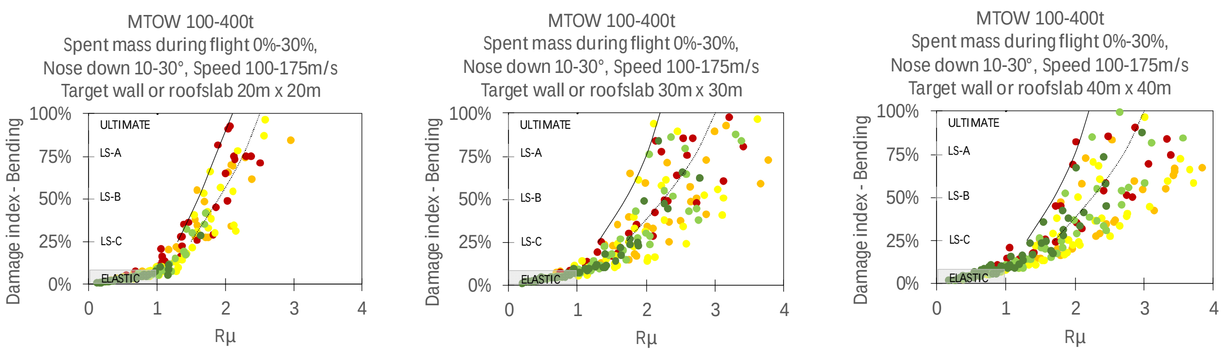


Figure 6. Calculated reduction factor in various scenarios and design configurations

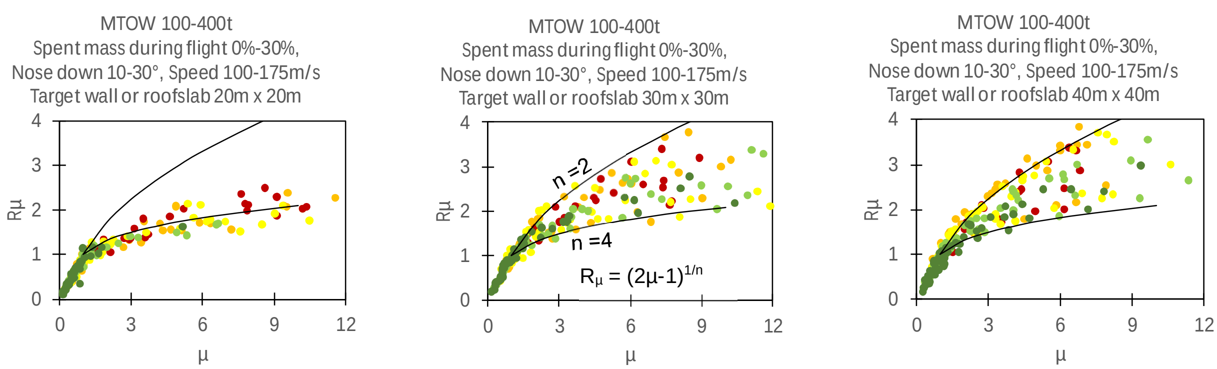
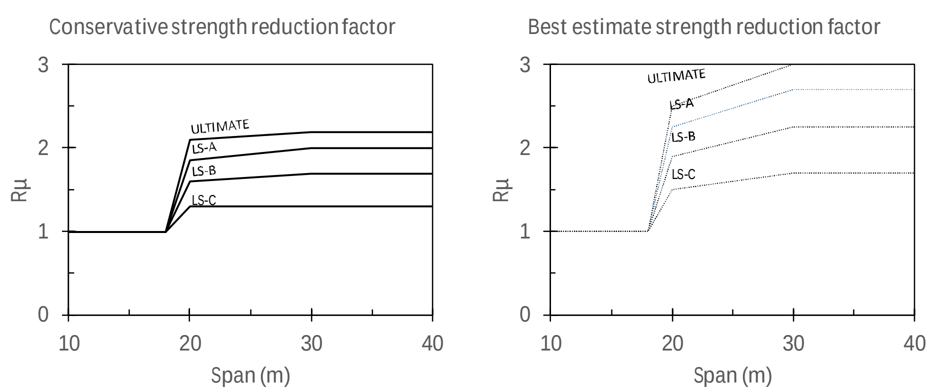


Figure 7. Relationship between reduction factor and ductility factor (color legend defined at Table 1)



Note : no ductility assumed when span < 10x thickness

Figure 8. Proposed reduction factor for use of pseudo-static method in large aircraft impact analysis, as a function of the limit state and the target dimensions

EXAMPLES OF APPLICATION

Example of a roof slab basic design

Aircraft input data: MTOW = 200 T ; v = 150 m/s ; nose-down angle 30°
Target input data: roofslab 30m x 30m
Safety requirements: damage index in bending <75% (= LS-A); no failure of stirrups in shear (no residual transversal cracks)

- Engineering charts method:

a) assumption full mass (impact right after take-off) à design#2 is acceptable ; design#1 is not acceptable in bending. So, the recommended principles at preliminary design stage are 1.50m concrete, rebars 2Φ32@200mm/side/dir, stirrups Φ14@200x400 (210kg/m^3)

b) assumption end-of flight (impact close to landing airport) à design#1 is acceptable. So, the recommended principles at preliminary design stage are 1.20m concrete, rebars 2Φ32@200/side/dir, stirrups Φ14@200x400 (260kg/m^3)

- Static method: $R_\mu = 2.7$ (best estimate) ; $\cos(\theta) = \cos(60°) = 0.5$

a) assumption full mass (impact right after take-off)
Thickness = 1.50m ; Frequency = 6 Hz ; $DLF.F_{max} = 350$ MN ; $F_{pseudo\text{-}stat} = 350 \times 0.5 / 2.7 = 64$ MN
Equivalent radius of impact area at mean fibre ≈ 4.5m
Rebars calculations in bending at center: $A_{s,inf} \approx 100$ cm²/m/dir. So, pseudo-static method remains slightly conservative compared to selected principles #2 at preliminary design: 2Φ32@200 = 80.4 cm²/m.

b) assumption end-of flight (impact close to landing airport)
Thickness = 1.20m ; Frequency = 5 Hz ; $DLF.F_{max} = 150$ MN ; $F_{pseudo\text{-}stat} = 150 \times 0.5 / 2.7 = 28$ MN
Equivalent radius of impact area at mean fibre ≈ 4.5m
Rebars calculations in bending at center: $A_{s,inf} \approx 60$ cm²/m/dir. So, pseudo-static method confirms that the selected principles #2 at basic design is adequate: 2Φ32@200 = 80.4 cm²/m.

This example shows that pseudo static-method provides correct order of magnitude for rebars calculations with error variability +/-25%. This comes essentially from the uncertainty in the reduction factor estimate (see great dispersion observed in Figure 8 for a given damage requirement).

- Elasto-plastic dynamic method:

Verifications are given here for the design principles #2. Time history calculations enables to observe that:
a) assumption full mass (impact right after take-off):
$\mu = 8.4$; $R_\mu = 3.7$; n = 2.1 ; bending damage index = 73% à ok ; stirrups state = elastic à ok

b) assumption end-of flight (impact close to landing airport):
$\mu = 2.1$; $R_\mu = 1.8$; n = 2.0 ; bending damage index = 11% à ok ; stirrups state = elastic à ok
This example shows that design #2 corresponds to damage level between 11% and 73%, depending on the time of impact during the flight, namely the remaining fuel payload. Same calculations with design #1 would show a damage level between 35% and >100%.

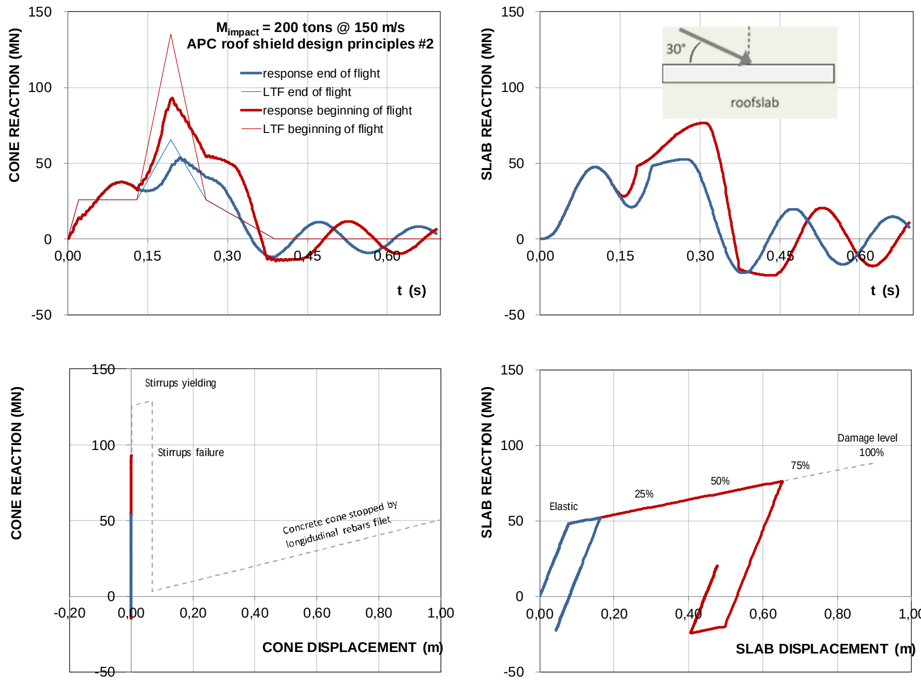


Figure 9. Example of design application on a roof slab

Example of reverse engineering

The charts can be used to make fast diagnosis of an existing building. Let's consider a 1.30m thick reinforced concrete shield, as indicated in EUR recommendations. Longitudinal rebars principles are assumed to be 2Φ32@200/side/direction. Dimensions 20m x 20m. This case is intermediate between design #1 (1.20m thick) and design #2 (1.50m thick). According to the charts, if the safety requirement is limit state A, namely 75% damage level (so as to keep a certain margin for uncertainties before ultimate failure), and no allowed stirrups failure, the capacity of the roof slab and the vertical walls are determined graphically for any mass of aircraft and any velocity. It can be stated that the capacity of the shield is limited: the smaller commercial aircrafts (MTOW <200tons) combined with relatively low speed (v<120m/s) represent the most severe acceptable conditions.

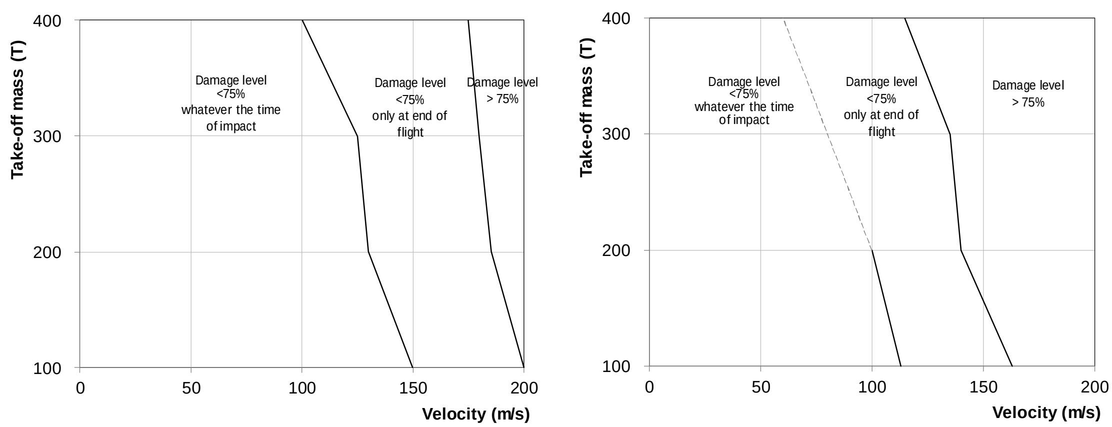


Figure 10. Example of APC diagnosis for a given design 1.30m thick shield.
Left: roofslab (aircraft nose-down 30°) ; Right: vertical wall (aircraft nose down 10°).

CONCLUSION

This paper introduced an efficient engineering methodology for design of aicraft impact on rectangular reinforced concrete buildings, based on the development of damage charts as a function of the main parameters of mass and velocity. The method can be used as well for diagnosis of existing structures. It was thought out in a standardization purpose and could be thereby inserted in civil design codes.

By analogy with seismic design, a relevant approach could be to follow different steps:

Deterministic design

- Definition of safety requirements in terms of aircraft take-off mass, kerosene gauge considering distance of the nuclear facility to the closest airport, impact velocity and acceptable damage level to the building.
- Materials strength of the reinforced concrete shield is considered at the characteristic value.
- Preliminary design in accordance with the charts or by pseudo-static method, for which dynamic load factors and plasticity reduction factors are proposed.
- Adjustments of steel rebars principles and concrete thickness:
    - Additional verification of steel liner strains at inner side (non-tearing if there is a liner)
    - Additional local verification by empirical formulations (penetration, scabbing)
    - Additional justifications related to fire requirements in post-impact static conditions (effects of high temperature on reinforced concrete strength)
    - Additional justifications related to kerosene fire management strategy (acceptance of transversal cracks)
- Basic design verifications by fast-dynamics finite element calculations using the normalized load time function and the preliminary design as input (decoupled method)

Probabilistic design assessment (analogy with seismic margin assessment)

- Definition of additional safety requirements in terms of high confidence low probability of failure velocity, and possibly in terms of cumulated probability of striking the target combined with ultimate failure of the shield.
- Materials strength of the reinforced concrete shield should be here considered at the median value.
- Verification by fragility analysis at ultimate limit state. Starting point of the analysis is given by the deterministic analysis with the help of the charts. Assessment of various margin factors and associated variabilities shall be done. This topic is developed into the twin paper “Part 2: Probabilistic fragility assessment”.

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.

ASCE/SEI 43-05, "Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities", *American Society of Civil Engineers.*

BEA (2015). "Final Report. Accident on 24 March 2015 at Prads-Haute-Bléone (Alpes de Haute Provence, France) to the Airbus A320-211 registered D-AIPX operated by Germanwings", *Bureau d'Enquêtes et Analyses pour la sécurité de l'aviation civile.* https://www.bea.aero/uploads/tx_elydbrapports/BEA2015-0125.en-LR.pdf

Blandford. E., et al. (2009). "Advanced seismic base isolation methods for modular reactors", *University of California, Berkeley, September 30, 2009, ref. UCBTH-09-004.*

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

Forasassi G., Lofrano R. (2010). "Preliminary analysis of an aircraft impact ", *Consorzio Interuniversitario Per La Ricerca Tecnologica Nucleare, Universita Di Pisa, CIRTEN-UNIPI RL 1059/2010* .

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 (2014), Draft Safety report DD1087. R3D1 "Safety Aspects of NPP Structures against Human Induced External Events: Assessment of Structures", *International Atomic Energy Agency.*

IAEA (2017a), Safety report No. 86 "Safety Aspects of Nuclear Power Plants in Human Induced External Events: General Considerations", *International Atomic Energy Agency.*

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

ITER (2012), *Structural Design Code for Buildings (I-SDCB) Part 1: Design Criteria*, 13 Jun 2012 / 2.10.

Korotkov, V.A. and Ivanov, A.P. (2013). "Applicability of Modal Dynamic Method in Seismic and Aircraft Crash Analyses of NPP Structures", *2016 Science in the Age of Experience.*

Kostov, M. and Andonov, A. (2013). "Load time function definition for large commercial aircraft impact: parametric study", *Transactions SMIRT22, San Francisco, California, USA – August 18-23, 2013 Division III.*

Kultsep, A., et al. (2013). "Load on structures due to large airplane impact", *Transactions SMIRT22, San Francisco, California, USA – August 18-23, 2013 Division III.*

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.*

Miranda, E. and Bertero, V.V. (1994). "Evaluation of strength reduction factors for earthquake resistant design". *Earthquake Spectra, Vol. 10, No. 2, 1994.*

NEI 07-13. Rev.8P, "Methodology for Performing Aircraft Impact Assessment for New Plant Designs, *Nuclear Energy Institute.*

Tieping Li., et al. (2019). "An engineering model and its numerical validation for a malevolent aircraft impinging against a rigid target: Force and impulse estimations", *Nuclear Engineering and Design, 342 (2019) 1-9.*

Wierzbicki T., et al. "Aircraft Impact Damage", *Essay on WTC, Massachusetts Institute of Technology.* http://web.mit.edu/civenv/wtc/PDFfiles/Chapter%20IV%20Aircraft%20Impact.pdf

"The 9/11 Commission Report", *National Commission on Terrorist Attacks on the United States, August 21, 2004.*

APPENDICES: ENGINEERING CHARTS

See next 4 pages. Colour legend is defined at Table 1 corresponding to five different design principles.

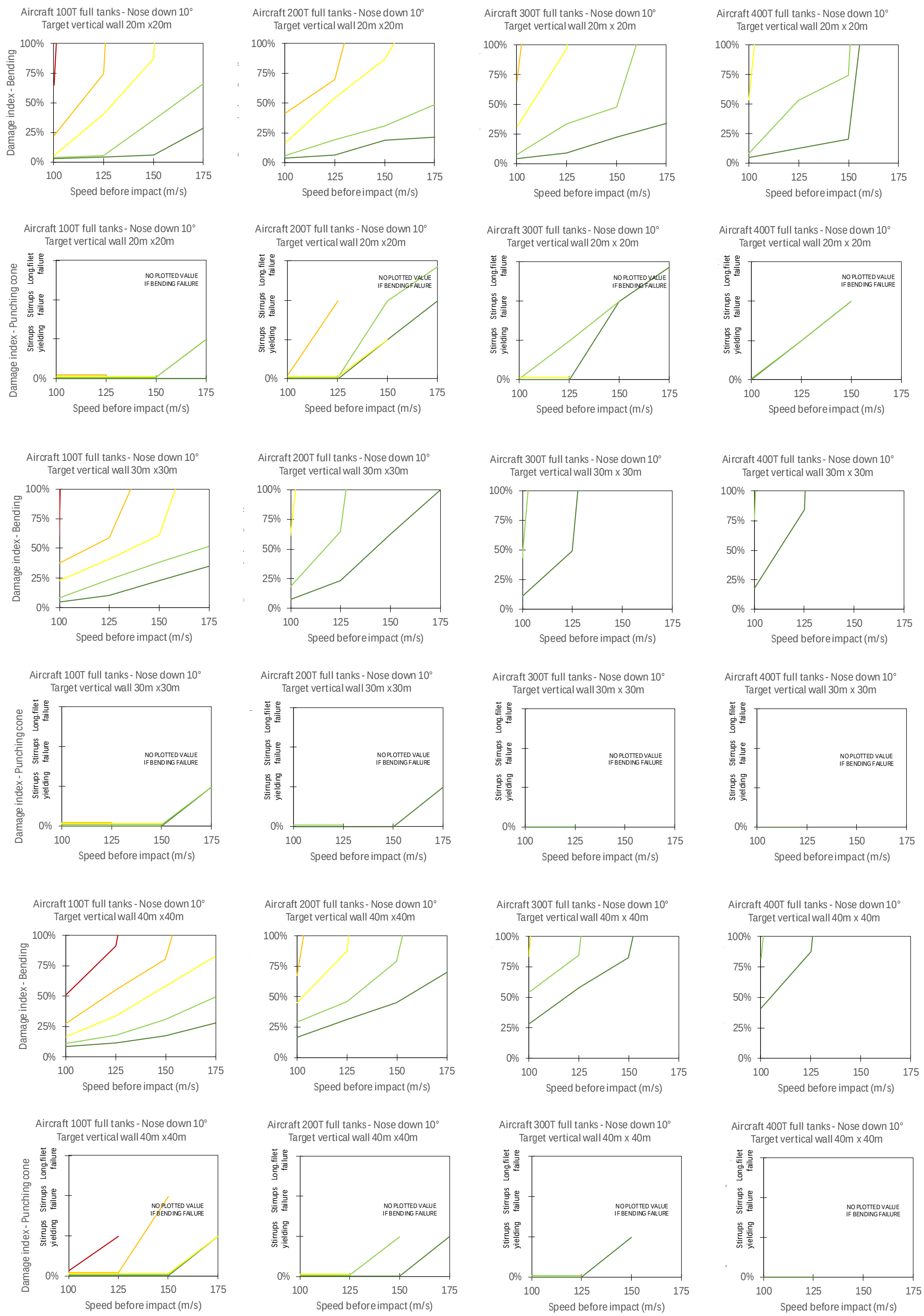
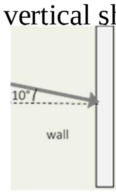


Figure 11. APC damage evaluation on vertical shield (**full tanks**, nose-down angle 10°)



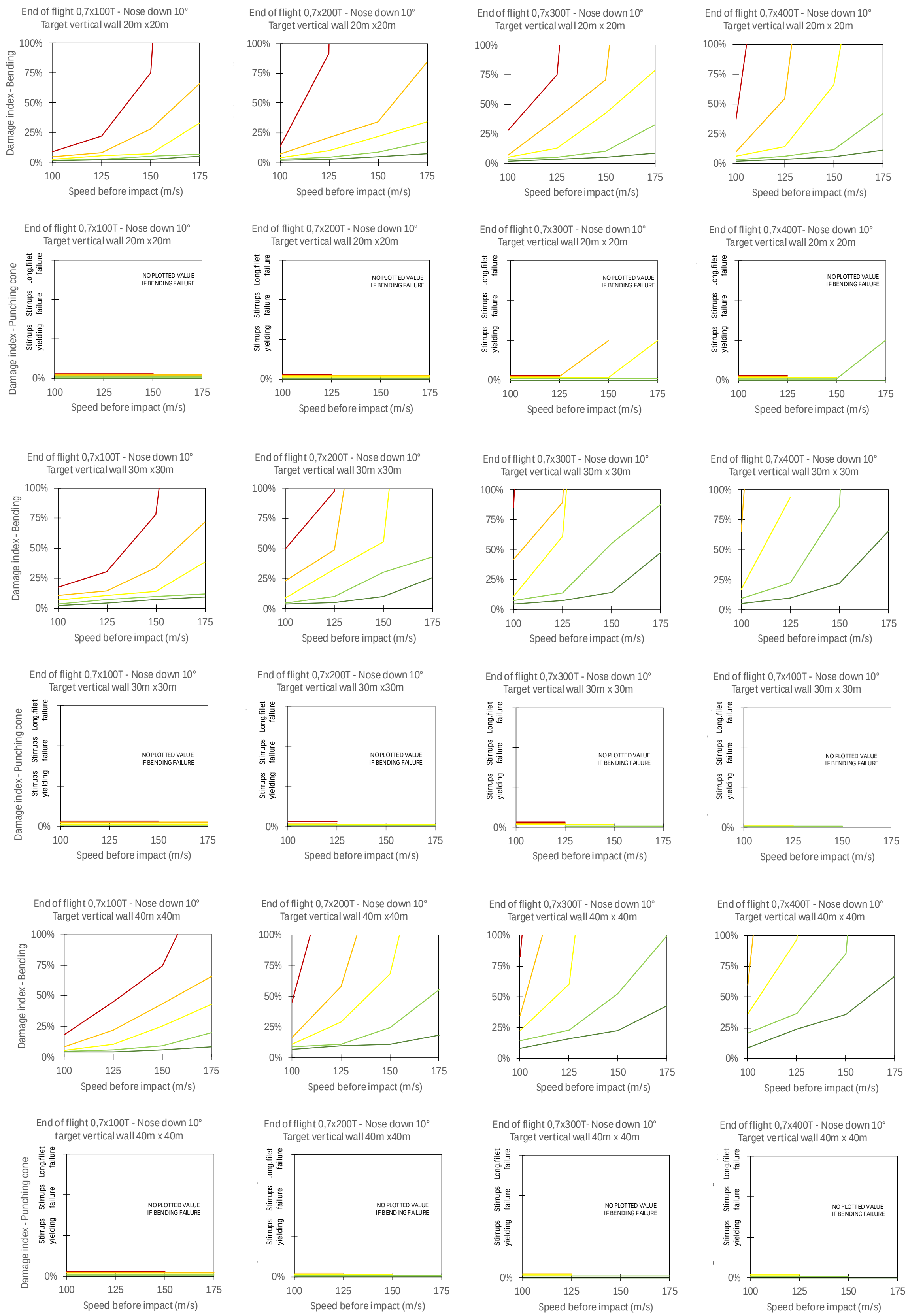
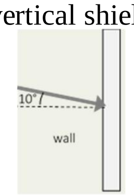


Figure 12. APC damage evaluation on vertical shield (**end-of-flight**, nose-down angle 10°)



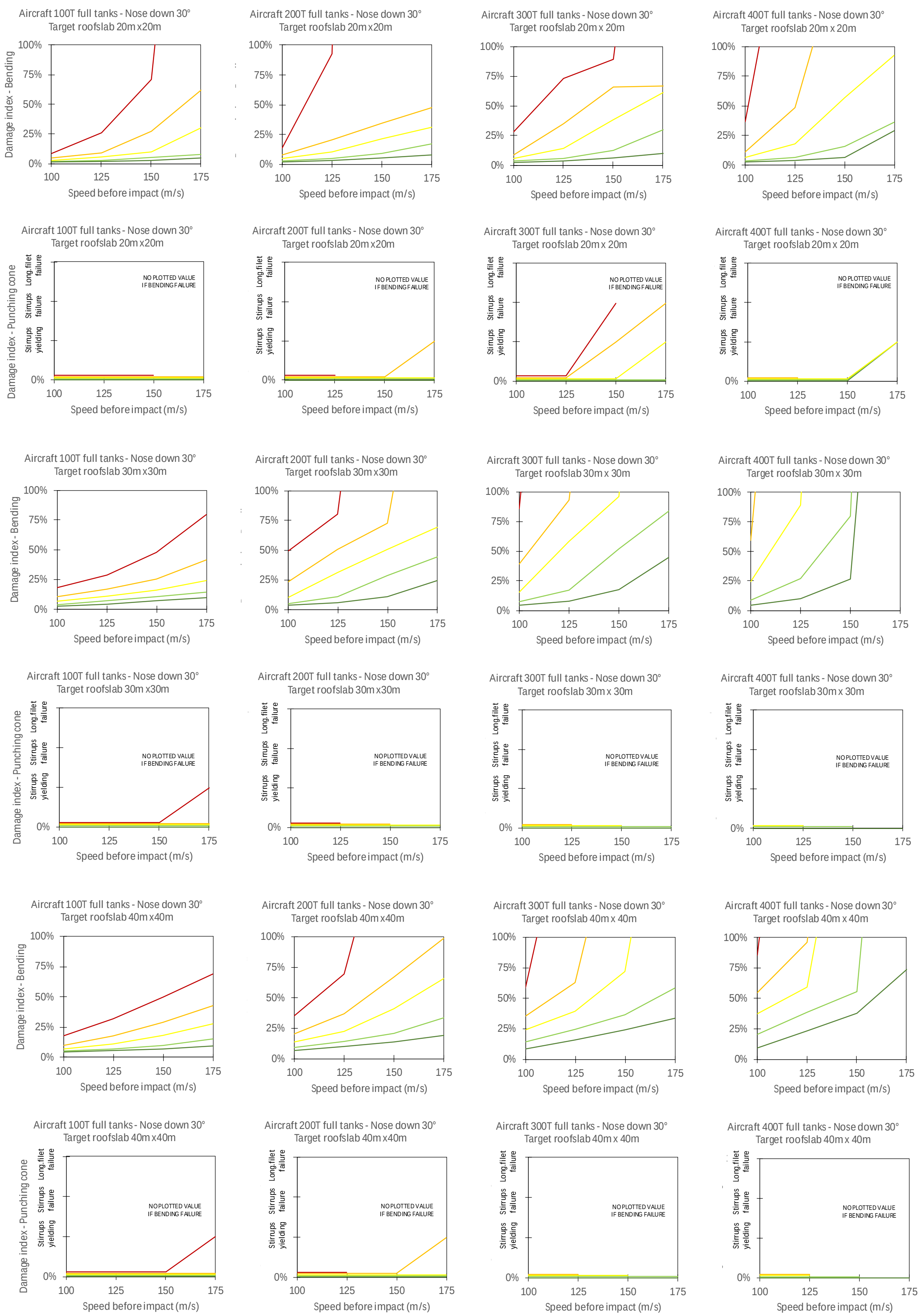
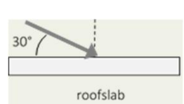


Figure 13. APC damage evaluation on horizontal roof shield (**full tanks**, nose-down angle 30°)



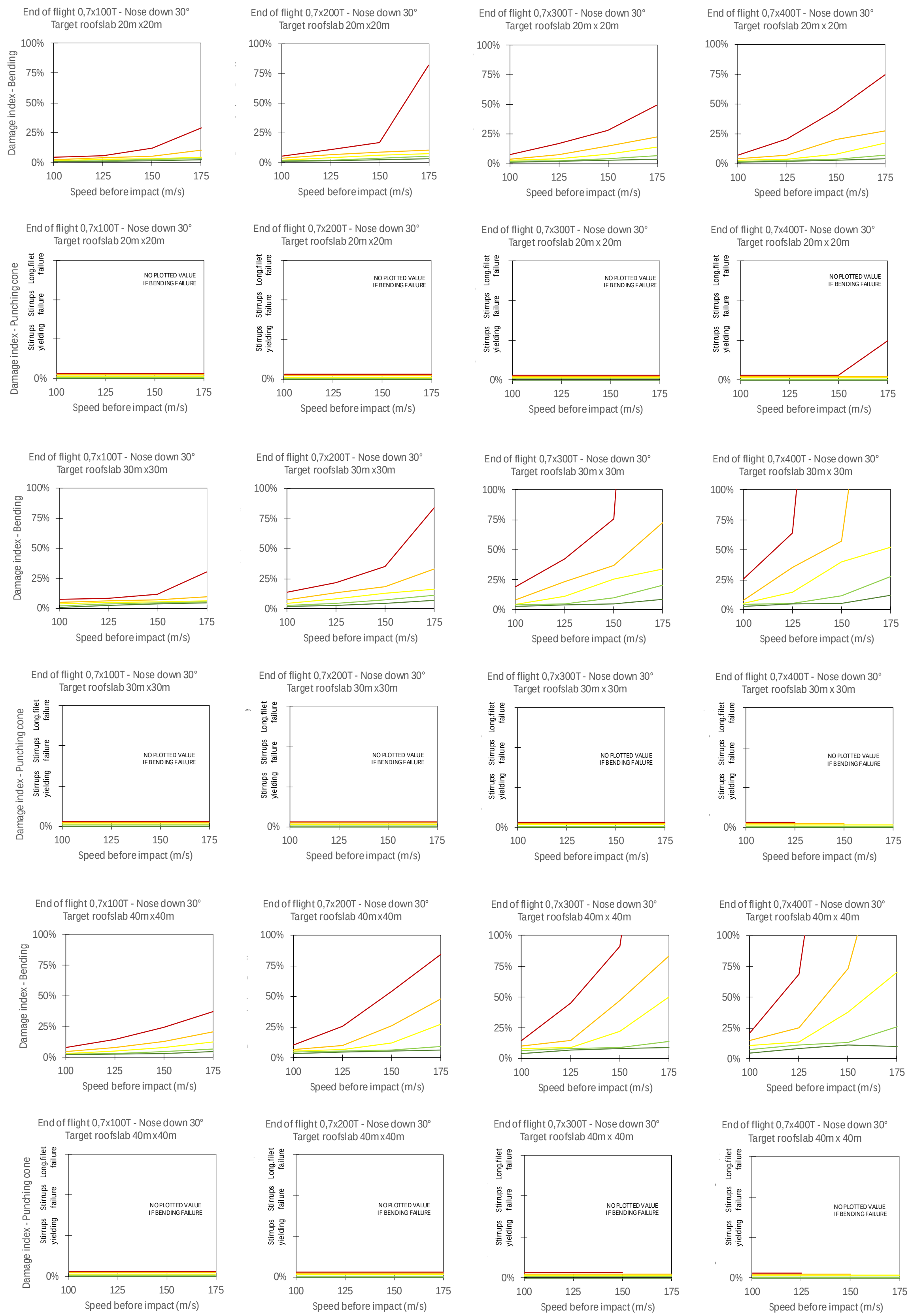


Figure 14. APC damage evaluation on horizontal roof shield (**end-of-flight**, nose-down angle 30°)