31st Congress of the International Council of the Aeronautical Sciences
Belo Horizonte, Brazil; September 09-14, 2018

STUDY OF ACCIDENTAL IMPACT SCENARIOS FOR COMPOSITE WING DAMAGE TOLERANCE EVALUATION

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Keywords: *damage tolerance, composite wing, threshold energy, impact damage, probabilistic analysis*

Abstract

The field data characterizing aircraft accidental in-service damage was collected, sorted and processed. By means of probabilistic analysis the wing damageability statistical parameters were determined. The scenarios of wing accidental impacts were described and the qualitative distribution of impact intensity over the wing surfaces was obtained. By means of original analytical method the metal dent depth data was converted into impact energy data and energy probabilistic distributions were established. For damage tolerance analysis the Rouchon probabilistic model was applied. It was shown that the functional relationships generated on domestic data are generally consistent with similar foreign results obtained on other types of aircraft with serious differences in operating conditions. Along with realistic impact damage scenarios the high energy impact events were considered. It was noted that in some cases severe damage events should not be addressed as extremely improbable and should be included into design and certification process.

1 Introduction

The problem of internal delamination caused by accidental impact is known to be the major challenge in aircraft composite primary structure safety provision. The most reliable way to learn the laws of impact damage formation is to study the operating experience related to in-service damageability.

One of the first studies on the classification of accidental impact damage was presented in the work of Sikorsky Aircraft Division in 1980 [1], where the damage tolerance approach for composite elements accepted later by majority of aircraft manufacturers has been proposed. In accordance with this method, the estimation of damage occurrence can be made basing on the type of damage expected during maintenance process.

The considerable input into a study of metal and composite aircraft structures accidental impact scenarios was made in studies [2-3] performed in the nineties of 20th century. The extensive research program focused on in-service damageability of US Navy fighters (Northrop and MCAir survey) became the basis for statistical analysis made by Kan et al. [2]. This database included 1644 dents registered on a metal structure of F-4, F-111, A-10 and F-18B aircraft and was used for development of a probabilistic approach for composite structures certification. Research of Gary and Riskalla [3] was also dedicated to the probabilistic design of composite structures and included statistical data on 1484 accidental damage from low-velocity impacts collected on the composite elements of aircraft of US domestic air carriers: Delta Airlines, United Airlines and American Airlines. Cumulative operating time analyzed in [3] totaled 3.8 million flight hours.

In 21st century aircraft manufacturers pay a lot more attention to the problem of impact damage threat. For damage tolerance certification of composite airframe the fleet experience with total flight time of more than 30 million F.H. was taken into consideration by Airbus [4-5]. One should also mention the domestic study [6] in which the service data of military and transport airplanes MiG-29, Sukoi 27 and Antonov 124 was summarized and analyzed by Ushakov et.al [6] for the development of structural safety probabilistic model.

The methodological basis developed in above studies established foundations of damage tolerance philosophy used for composite primary structures nowadays.

2 Methodology

2.1 Damage Tolerance Approach

The modern damage tolerance approach accepted for airframe composite structures requires that any impact damage in the composite structure either should be detected or should not reduce the structural strength below ultimate load capability. This approach is described in Advisory Circular [7] and based on the five category classification of the damage potentially expected in operation. Damage is classified depending on the detectability, or more specifically - depending on the operating time needed for reliable detection of this damage within the accepted aircraft maintenance program. For each category, the requirements for static and fatigue loads are established, which the damaged structure must withstand while operating up until the moment of damage detection. The Category 1 addresses non-detectable damages and limited by two thresholds: threshold of detectability (known as barely visible impact damage) and energy threshold ("realistic" energy level) whichever comes first. The Categories 2 and 3 addresses visible impact damages and damages caused by the severe impacts.

There are at least two ways to identify which energy level can be considered as "realistic" and each one has been accepted by certification authorities of FAA and EASA.

According to the deterministic approach, the energy thresholds are to be evaluated basing on prescribed impact parameters: impacted zone of structure, impact energy and frequency of event. First, this approach was applied by Cook [1] for the zoning of a military helicopter fuselage: for each zone depending on the expected frequency of events which may potentially lead to impact damage (mostly caused by maintenance procedures), the energy exceedance curves were generated and considered as damage tolerance criteria. Later this approach was developed by Kan et al. [2] who investigated the relationship between low velocity impacts energies and damage sizes in wing panels of different thickness. As a result of these studies the value of 100 ft-lbs (136 Joules) was adopted for the realistic energy threshold.

Probabilistic approach proposed by Rouchon [8] implies the determination of the realistic energy level on the basis of in-service statistical data relevant to actual operating conditions. This approach was used in the current study for the estimation of wing damage tolerance parameters.

2.2 Field Survey

Design of MS-21 aircraft with full composite wing has led to urgent need of advanced certification approach [9]. As a part of this approach the in-house studies on impact threats scenarios typical for local operational conditions were initiated.

On the first stage of those studies Feygenbaum and Dubinskii [10] performed the analysis of 1258 damage events registered in operation and during maintenance of commercial fleet. The work was continued by the team of experts from industry research institutes and airlines who collected and analyzed data on accidental damages registered between 2000 and 2016. The data came from periodic reviews of structure for airworthiness, operator's reports, maintenance checks, failure registration cards, manufacturer databases, reports on structural condition assessment needed for service life extension and other documents containing relevant information.

About 30 thousands documents related to 35 aircraft types were reviewed to identify approximately 5300 damage incidents of various source and nature from barely visible surface deformations and scratches to very large damage causing a real threat to the structural integrity of airframe. Of these, about 2000 damage records were made on local fleet aircraft types (Ilyushin, Antonov, Tupolev, and Yakovlev) and about 3300 records on Boeing airplanes used by local operators. The operating time of the considered fleet totaled about 4 million flight cycles (F.C.) and 10 million flight hours (F.H.) The majority of damage was related to errors during ground handling: falling baggage, dropped tools, collisions with airfield infrastructure and ground service vehicles. For the purposes of current study only the wing skin surface dents were taken into consideration since this type of damage provides possibility to recover impact energy from dent geometry which is required for damage tolerance analysis.

2.3 Probabilistic model

In order to evaluate the probability of accidental in-service impact into wing of commercial aircraft the following simple probabilistic model was used.

The in-service damageability of the aircraft is considered as a random stream of events taking place in time one after another. It is assumed that damage events occur independently (the occurrence of one event does not affect the probability that a second event will occur), that damage events occur at constant rate and that two events cannot occur at exactly the same instant. Under those assumptions the exponential distribution can be applied:

$$f(t)=\lambda e^{-\lambda t} \quad (1)$$

and the damage probability function P_D can be expressed as:

$$P_D(t) = \left(1 - e^{-\lambda t}\right) \quad (2)$$

Here t is time, λ is damage intensity, - parameter, inverse to average flight time until damage event T measured in F.H. or F.C.:

$$\lambda = 1/Tf \quad (3)$$

The damage intensity for the given aircraft type averaged on the fleet is:

$$\bar{\lambda}_i = N_i/T_{\Sigma i} \quad (4)$$

Here N_i is the total number of registered damage for all airplanes of type i, $T_{\Sigma i}$ – total flight time measured in F.H. or F.C. In Table 1 the average flight time until damage and damage intensity for 16 aircraft types is presented.

Table 1

It follows from Table I that the damage intensity per F.H. averaged on the full data set makes:

$$\bar{\lambda} = \sum_{i=1}^{n} N_i \Big/ \sum_{i=1}^{n} T_{\Sigma i} = 5{,}43 \cdot 10^{-4} \quad (5)$$

Taking into account that in-service impacts are known to be the major damage threat for composite structures [4,8] and assuming that the primary signature of accidental impact into metal skin is the surface dent formation it will be reasonable for the purposes of composite wing damage tolerance evaluation to limit the analysis of developed field survey by the type of damage having form of dent.

For the qualitative characterization of wing damageability it was proposed to divide aircraft wing into zones and determine the impact threat for each one. The generic wing structure of commercial aircraft consists of wingbox, leading edge, trailing edge, wing to body fairing, flaps, slats, ailerons, interceptors, airbrakes and wingtips. Where applicable the inboard / central / outboard parts of each element were allocated and for each part the top and bottom surface were considered separately. In total it made $N_z = 34$ zones of the wing, see Table II.

The impact threat for each zone was estimated by methods of conditional probability analysis. (The conditional probability is a measure of the probability of an event given that another event has occurred [11]). In the current case it means that in order to evaluate the conditional probability of the impact into given zone of the wing element $\bar{p}_z^n$ one should take into account the following probabilities:

- averaged probability $\bar{p}_e$ that the wing element is damaged given that the airframe damage occurred;
- averaged probability $\bar{p}_{dent}$ that the wing element is impacted (damage has the form of surface dent) given that the wing element is damaged;
- probability p_{sq}^n that zone n is impacted given that the wing element containing zone n is impacted.

$$\bar{p}_z^n = \bar{p}_e \cdot \bar{p}_{dent} \cdot p_{sq}^n \qquad (6)$$

$$\bar{p}_e = n_e / N_\Sigma,\ \bar{p}_{dent} = n_{dent} / N_e, \quad (7)$$
$$p_{sq}^n = s_n / S_{element}$$

Here n_e is number of wing damage events, N_Σ is the total number of damage events, n_{dent} is number of dents on the wing element, N_e is the total number of damage of all types registered on the element, s_n is the area of the zone n, $S_{element}$ is the total area of the wing element containing zone n.

The conditional probabilities of the accidental impact into the allocated zones of the wing averaged on all considered aircraft types are presented in Table 2. Here $\bar{p}_{zn}^n$ is the $\bar{p}_z^n$ normalized per unit.

Table 2

the similar estimations made by other authors, it is necessary in accordance with Rouchon model [8] to determine the probability of impact into wing:

$$P_{impact} = \left(1 - exp\left(-\sum_{n=1}^{N_z=34} \bar{p}_z^n \cdot \bar{\lambda}\right)\right) = \left(1 - exp\left(-0.2097 \cdot \bar{\lambda}\right)\right) \cong 10^{-4} \qquad (8)$$

This expression is derived from equation (2) for $t = 1\ F.H.$, where $\sum_{n=1}^{N_z=34} \bar{p}_z^n$ is conditional probability of whole wing structure impact damage.

The distribution of $\bar{p}_{zn}^n$ over the wing structure provides possibility to have the picture of wing relative damageability and understand in which zones of the wing the impact threats are more likely. On the Fig. 1 one can see the qualitative distribution of impact intensity over the top and bottom surfaces of the wing.

Figure 1

It follows from Fig.1 that the wing panels are the least prone to damage, as the main risk of collision with objects is related to wing edges. Slat and inboard flap are most damaged elements of the wing: the damage comes from flight hail, runway debris, errors during taxiing, collisions with ground service equipment (GSE) and aerodrome structures.

2.4 Impact Energy Distribution

Statistical data on accidental impact damage collected on metal aircraft skins can be used for damage tolerance evaluation of similar composite structures. In order to do this it is necessary to convert the metal dent depth into impact energy. For this purpose the original analytical method [12] based on the establishment of three-dimensional relationship between the impact energy, dent depth and thickness of the skin was developed. The relationship for duralumin alloy 1163 which is used in skin panels of most aircraft types, mentioned above was generated and validated experimentally. The impact cases valid for conversion were selected from the damage database and translated into impact energy survey. The resulting energy range covered three orders of magnitude, from a few joules to several thousand joules.

Unlike the Northrop and MCAir survey analyzed by Kan et al. [2], the TsAGI and GosNII GA database includes a significant number of high energy impact events. For damage tolerance analysis it would be reasonable to make the same data extraction as in Northrop and MCAir study where the depth of registered metal dents did not exceed 0.1 inches (2.5 mm). The cumulative probability distributions (probability to encounter the impact energy E or less) for full and for limited data samples are shown on Fig. 2-3.

The empirical distribution of full data sample (Fig. 2) is very close to a logarithmically linear function. The hypothesis, that impact energies are distributed according to logarithmically normal law, was checked by $n\omega^2$ criterion for two unknowns [13]. The calculated statistic value $n\omega^2 = 0.1215$ appeared to be less than the criterion value $(n\omega^2)_\alpha = 0.125$ taken at the accepted significance level $\alpha = 0.05$ [14]. Thus hypothesis about normality of experimental data has been confirmed at a significance level of 5% or more. The Weibull function established from the same data it does not agree with the empirical distribution (Fig. 3).

The distribution of limited empirical data sample agrees neither with Lognormal nor with Weibull distribution: both hypotheses have too low significance level $\alpha < 0.001$ by the Anderson-Darling criterion [15]. It follows from Fig. 3 that the left-hand side is better described by the Weibull distribution and the right-hand side - by Lognormal law. Thus for the limited data sample of the given survey there is no definite distribution law, it can only be stated that Weibull distribution can be reasonably used for small energies while Lognormal distribution is more suitable for moderate energy impacts consideration.

Figures 2,3

3 Damage Tolerance Analysis

Though it is reasonable to assume that for determination of realistic impact energy level the use of limited data sample is more adequate than use of full data sample which includes such unrealistic events as serious collision with airfield buildings, equipment, GSE and other airplanes, for the purposes of damage tolerance analysis both data samples were considered. The reason for full data sample analysis importance is that the sampling criteria taken from the Northrop and MCAir survey, in which dents larger than 2.5 mm were not registered at all, may be not always be valid for composites. If one assumes that at least one high energy impact event remains unreported or ignored by technical personnel during aerodrome maintenance it is reasonable to make estimation on the full data sample.

According to Rouchon model [8] and approach presented in Handbook [16] the probability $P(E)$ to encounter an impact in operation with an energy exceeding E is the product of two independent probabilities: the probability of obtaining an impact in operation P_{impact} and the probability of exceeding a certain level of energy $P_E(E)$:

$$P(E) = P_{impact} \cdot P_E(E) \qquad (9)$$

The empirical distributions of $P(E)$ determined on the basis of TsAGI and GosNII GA impact energy survey for two P_{impact} estimations (the first one $P_{impact} = 10^{-4}$ derived above from local field data, see equation (8), and the second one $P_{impact} = 10^{-3}$ taken from Gary [3] and Airbus [4] studies) are shown on Fig.4. The limited and full data sample distribution functions were approximated respectively by Weibull and Lognormal laws.

Figure 4

According to advanced non-conservative damage tolerance methodology developed by Airbus [4] and approved by certification authorities of FAA and EASA, the "realistic" and "severe" energy levels can be derived from energy distribution function under the following assumptions.

The impact with "realistic" or higher energy aircraft may experience not more often than once per lifetime. Taking service life of modern aircrafts for 10^5 F.H., the probability of "realistic" energy level can be determined as $P(E_{realistic}) = 10^{-5}\ F.H.$ The "severe" or "maximum possible" energy level may be determined by criterion of almost improbable event, namely 10^{-9}: $P(E_{maximum}) = 10^{-9}\ F.H.$ Using the relationships from Fig.4 the energy levels corresponding to those probabilities were determined, the summary results are presented in Table 3

Table 3

“Realistic” scenarios, (Fig.4 a). Under the assumption that all high energy impacts are immediately reported the limited data sample should be used for damage tolerance analysis. The impact energy which aircraft may encounter during its lifetime determined for conservative case $P_{impact} = 10^{-3}$ makes $E_{realistic} = 36\,J$. This figure matches Airbus threshold value $E_{realistic} = 35\,J$ [4] which was determined under the same assumptions but on very different data set, namely Northrop and MCAir survey of US Navy fighters. The $P(E)$ distribution calculated for US Navy data [2] is also shown for comparison. The trend lines on Fig.4 a) confirm that impact of 136 J accepted as a threshold value in Boeing damage tolerance methodology [17] can be considered as a remote event.

“Unrealistic” scenarios, (Fig.4 b). Under the assumption that any damage in the wing structure may remain undetected for considerably long time comparable with heavy inspection interval the full data sample can be applied for damage tolerance analysis. In the conservative case ($P_{impact} = 10^{-3}$) the “threshold” energy exceeds thousand joules and the probability of exceeding of 136 J makes only 10^{-4}, which means that the aircraft can encounter an impact with energy over 136 J about ten times per service life.

3 Discussion

On the one hand improbable events may not be considered as applicable data for evaluation of “realistic” energy threshold and thus the estimations made in Table III on full data sample are ultraconservative and for the first look are not adequate. On the other hand, domestic experience shows that for various reasons even very serious incidents can be left unreported, which is much more dangerous for composites than for metal structures because of hidden internal damages. The following example related to wing damage event from TsAGI and GosNII GA field survey can be mentioned. It is known that the critical design case for the composite wing is compression after impact. The well-known sources of impacts for upper wing panel (compressed zone) are standard tool drop, tool box drop and walking on the prohibited areas. However, along with the aforementioned sources the performed analysis revealed another dangerous scenario which was never taken into account. It appears that the severe damage to the upper panel may be caused by the impact of a deicing hand on the ramp right before aircraft departure. It is expected that such kind of event should be immediately reported, but unfortunately the field experience indicates the opposite. Another example is High Energy Wide Area Blunt Impact phenomena which recently became a matter of concern for FAA [18]. Those facts confirm that in some cases severe events should not be addressed as extremely improbable and make the consideration of unrealistic impacts part of design and certification process.

In the frameworks of certification process the structural safety for all scenarios expected in operation during the aircraft life cycle should be demonstrated. But should all of the noted scenarios be taken into account for design and maintenance program development? The operational manuals provide clear guidance on aircraft maintenance procedures and are specifically designed to minimize errors in ground handling. It is also assumed that airfield personnel do not intentionally damage airplanes. In the same time the missing of large internal damage in composite primary structure may lead to catastrophic situation. The solution of this problem should be based on an integrated approach in the design, certification and operation phases: introduction of advanced techniques of structural health monitoring, arrangement of training courses focused on composite structures maintenance, inclusion of conditional inspections to the Aircraft Maintenance Manual and an understanding of the rare but not improbable damage scenarios.

As for realistic scenarios, considered of on the basis of TsAGI and GosNII GA limited energy data, the analysis resulted in very similar to

Airbus [4] estimation of energy cut-off despite differences in origin of field data (US Navy fighters versus Russian commercial planes), energy recovery method (experimental calibration of dents on full scale wing versus three-dimensional relationship established analytically and verified on components [12]) and applicable probabilistic distribution (Weibull versus Lognormal).

4 Conclusion

The study of field impact survey containing the broad range of damage events registered on Russian commercial fleet for more than 15 years provided possibility to make the following conclusions.

The Rouchon method [4,8] to a big extent is invariant to data type and thus has wide scope of application in statistical analysis.

The threshold value of 136 J accepted by many manufacturers for the category of undetectable defects can be considered sufficiently reliable provided that aerodrome personnel have proper received training and understand the conditional inspections required for GSE strikes.

Depending on accepted assumptions the analysis of the same data may lead to results that differ from each other by orders of magnitude. The assumption that damage may be missed in operation leads to an energy threshold value that is greater (i.e. more conservative) than accepted in Airbus [4] and even Boeing [17] damage tolerance methodology.

Thus the significance of obtained results is determined by the fact that they reflect realistic maintenance conditions which should eliminate extra conservatism in composite design but in the same time take into account severe scenarios for balancing of too optimistic approach. Basing on this study the damage tolerance parameters for composite wing of commercial aircraft can be reliably substantiated and new steps to increase weight efficiency of composite structures providing required level of safety can be made.

5 Copyright Issues

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Table I

Average flight time until damage and damage intensity for different aircraft types

i	Aircraft type	Number of damage events N_i	Total flight time		Average flight time until damage $T_{\Sigma i}$		Damage intensity, $\bar{\lambda}_i$	
			F.H.	F.C.	F.H.	F.C.	F.H.$^{-1}$	F.C.$^{-1}$
1.	Antonov 124	361	189201	44554	524.10	123.42	1.91•10^{-3}	8.10•10^{-3}
2.	Antonov 26	50	333137	173199	6662.74	3463.98	1.50•10^{-4}	2.89•10^{-4}
3.	Antonov 24	142	1084536	561827	7637.58	3956.53	1.31•10^{-4}	2.53•10^{-4}
4.	Antonov 12	98	198609	60342	2026.62	615.73	4.93•10^{-4}	1.62•10^{-3}
5.	Yakovlev 42	258	669690	302361	2595.70	1171.94	3.85•10^{-4}	8.53•10^{-4}
6.	Yakovlev 40	75	669690	302361	8929.20	4031.48	1.12•10^{-4}	2.48•10^{-4}
7.	Tupolev 204/214	40	397525	99116	9938.13	2477,90	1.01•10^{-4}	4.04•10^{-4}
8.	Tupolev 154	554	3140130	1290513	5668.11	2329.45	1.76•10^{-4}	4.29•10^{-4}
9.	Tupolev 134	153	1535327	804717	10034.82	5259.59	9.96•10^{-5}	1.90•10^{-4}
10	Ilyushin 96	120	299165	49851	2493.04	415.42	4.01•10^{-4}	2.41•10^{-3}
11	Ilyushin 86	98	417542	129373	4260.63	1320.13	2.35•10^{-4}	7.58•10^{-4}
12	Ilyushin 62	75	357900	73637	4772.00	981.83	2.10•10^{-4}	1.02•10^{-3}
13	Boeing 767-200	360	20784	6273	57.57	17.38	1.74•10^{-2}	5.75•10^{-2}
14	Boeing 737-800	408	123981	40260	303.88	98.68	3.29•10^{-3}	1.01•10^{-2}
15	Boeing 737-500	1345	347752	147424	258.55	109.61	3.87•10^{-3}	9.12•10^{-3}
16	Boeing 737-400	1140	55944	25488	49.074	22.36	2.04•10^{-2}	4.47•10^{-2}
	Total	**5277**	**9840913**	**4111296**				
	Average				**1842.87**	**769.91**	**5.43•10^{-4}**	**1.30•10^{-3}**

Table II
Conditional probability of wing element impact damage for different aircraft types

n	Wing element	Zone		$\bar{p}_z^n$	$\bar{p}_{zn}^n$
1.	Leading edge	Inboard	Bottom	0.0068	0.0230
2.			Top	0.0031	0.0103
3.		Outboard	Bottom	0.0005	0.0018
4.			Top	0.0025	0.0085
5.	Wingbox	Inboard	Bottom	0.0025	0.0083
6.			Top	0.0018	0.0058
7.		Center	Bottom	0.0010	0.0033
8.			Top	0.0006	0,0012
9.		Outboard	Bottom	0.0026	0.0086
10.			Top	0,0004	0.0015
11.	Trailing edge	Inboard	Bottom	0.0006	0.0019
12.			Top	0.0150	0.0502
13.		Center	Bottom	0.0003	0.0009
14.			Top	0.0015	0.0052
15.		Outboard	Bottom	0.0050	0.0169
16.			Top	0.0102	0.0343
17.	Wingtips		Bottom	0.0146	0.0487
18.			Top	0.0037	0.0124
19.	Wing to body fairing		Bottom	0.0021	0.0070
20.			Top	0.0043	0.0144
21.	Ailerons		Bottom	0.0079	0.0263
22.			Top	0.0041	0.0137
23.	Flaps	Inboard	Bottom	0.0169	0.0566
24.			Top	0.0328	0.1100
25.		Center	Bottom	0.0105	0.0354
26.			Top	0.0010	0.0302
27.	Slats	Inboard	Bottom	0.0148	0.0495
28.			Top	0.0259	0.0865
29.		Center	Bottom	0.0174	0.0584
30.			Top	0.0176	0.0591
31.		Outboard	Bottom	0.0206	0.0691
32.			Top	0.0246	0.0824
33.	Interceptors		Top	0.0035	0.0116
34.	Air brakes		Top	0.0140	0.0469
	Total			**0.2907**	**0.9999**

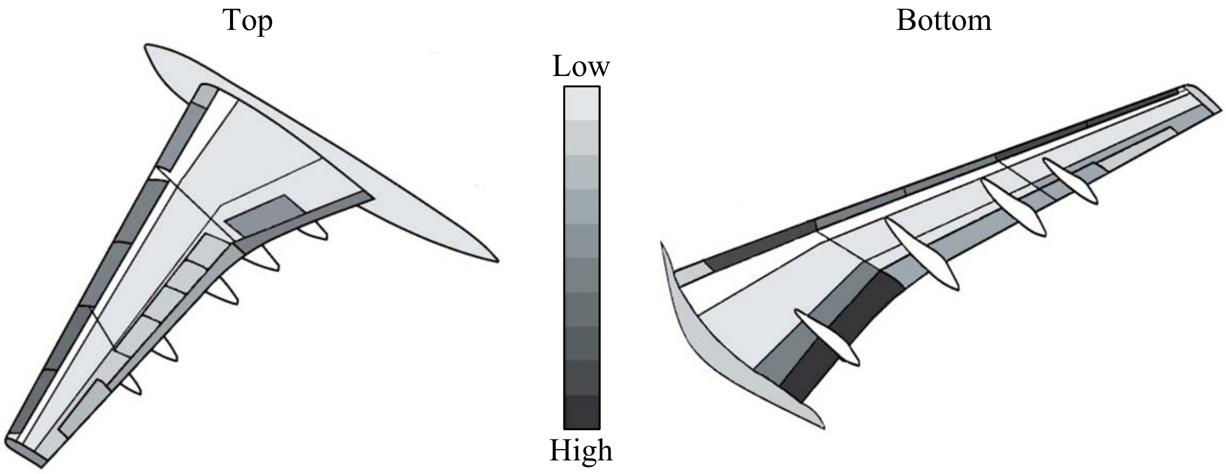

Fig. 1 Wing relative damageability $\bar{p}_{zn}^{n}$

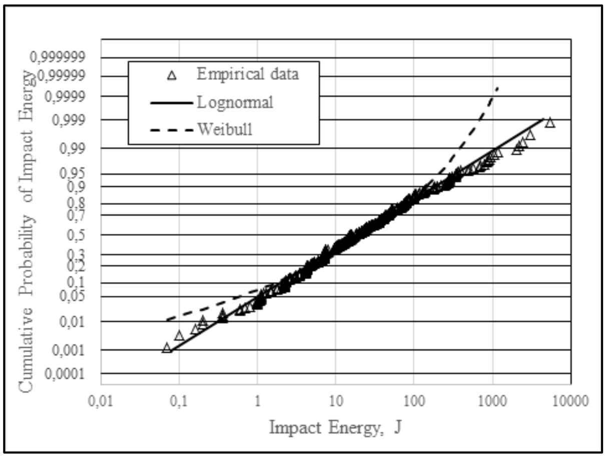

Fig. 2 Cumulative impact energy probability for full data sample (Lognormal scale)

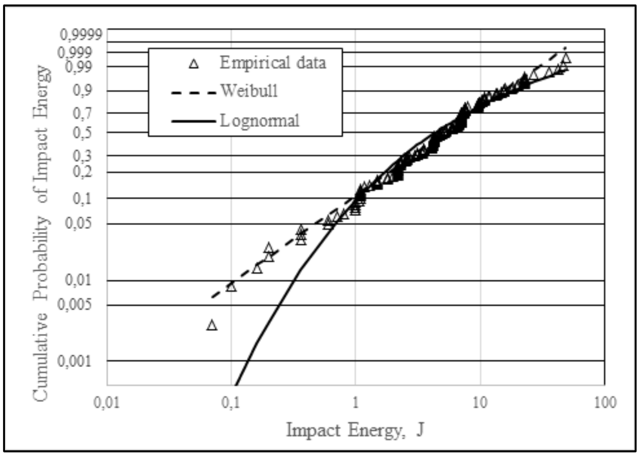

Fig. 3 Cumulative impact energy probability for limited data sample (Weibull scale)

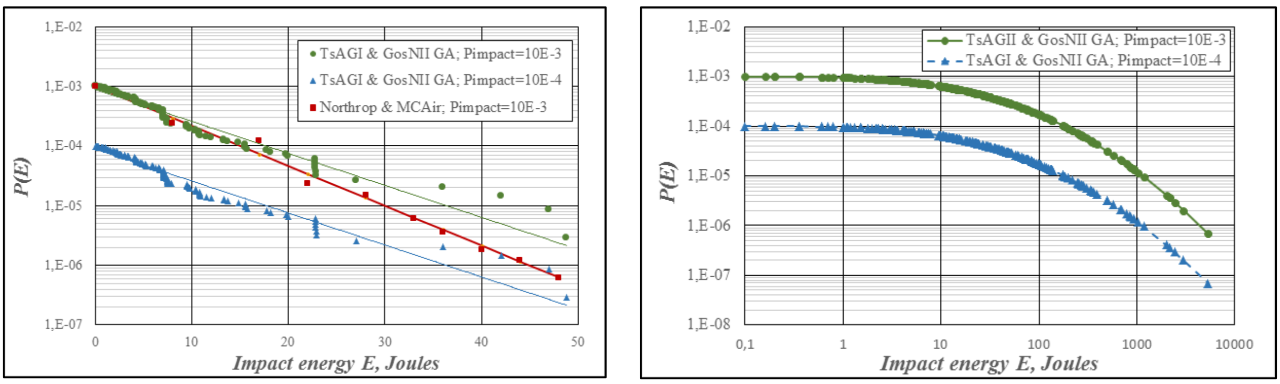

Figure 4 The $P(E)$ function: probability to encounter in operation an impact with an energy exceeding E

a) Limited data sample (Weibull law) *b) Full data sample (Lognormal law)*

Table III. "Realistic" and "Maximum" energy levels determined according to probabilistic approach [8]

	Boeing [13] (deterministic)	Airbus [4]	TsAGI and GosNII GA			
			Limited data sample		Full data sample	
P_{impact}	n.a.	10^{-3}	10^{-3}	10^{-4}	10^{-4}	10^{-3}
$E_{realistic}$ $(P=10^{-5})$	136 J	35 J	36 J	18 J	180 J	1140 J
$E_{maximum}(P=10^{-9})$	n.a.	90 J	110 J	100 J	n.a.	n.a.