A study of accidental impact scenarios for composite wing damage tolerance evaluation

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ABSTRACT

The field data characterising 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 were converted into impact energy data and energy probabilistic distributions were established. 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.

Keywords: Damage tolerance; Composite wing; Threshold energy; Impact damage; Probabilistic analysis

NOMENCLATURE

α	the significance level
N	number of registered damage events
T	total flight time until damage in cycles or flight hours
λ	damage intensity
$E_{\text{realistic}}$	impact energy related to realistic event
E_{maximum}	impact energy related to remote (extremely improbable) event
$(n\omega^2)_\alpha$	the magnitude of $n\omega^2$ criterion at significance level α
$P(E)$	probability to encounter an impact with an energy exceeding a given value of E
P_E	probability of exceeding of energy E
P_{impact}	probability of obtaining an impact in operation
P_{maximum}	probability of extremely remote event
$P_{\text{realistic}}$	probability of realistic event

1.0 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 based 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 1990s of the 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 1,644 dents registered on a metal structure of F-4, F-111, A-10 and F-18B aircraft and was used for the 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 1,484 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 analysed in the report[3] resembled 3.8 m flight hours.

In the 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 m flight hours 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 aircraft MiG-29, Sukoi 27 and Antonov 124 were summarised and analysed by Ushakov et al[6] for the development of structural safety probabilistic model.

The methodological basis developed in the above studies established foundations of damage tolerance philosophy used for composite primary structures nowadays. Following this approach, in the current study, for the purposes of damage tolerance analysis, the statistical data collected from the Russian aircraft fleet were interpreted and the input for characterisation of composite wing accidental impact scenarios was provided.

2.0 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 circulars[7,8] 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, in 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 address 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 is recognised as applicable according to Advisory Circulars of FAA[7] and EASA[8].

According to the deterministic approach, the energy thresholds are to be evaluated based on the 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 UH-60A Black Hawk helicopter: for each zone of the fuselage, the impact energy exceedance curves were generated and taken as damage tolerance criteria (the considered impact threat scenarios were mostly related to mistakes during standard maintenance procedures). 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 J) was adopted for the realistic energy threshold.

Probabilistic approach proposed by Rouchon[9] 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.
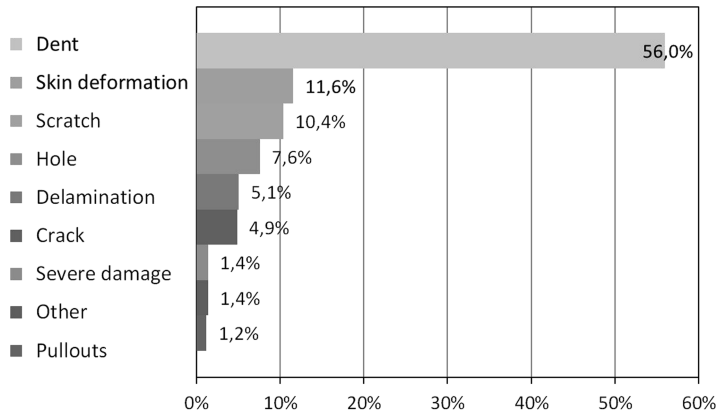
Figure 1. Breakdown of field damage data sources.

2.2 Field survey

Design of MS-21 aircraft with full composite wing has led to urgent need of an advanced certification approach[10]. As a part of this approach the in-house studies on impact threat scenarios typical for local operational conditions were initiated.

On the first stage of those studies, Feygenbaum and Dubinskii[11] performed the analysis of 1258 damage events registered in operation and during maintenance of a commercial fleet. The work was continued by the team of experts from industry research institutes and airlines who collected and analysed data on accidental damages registered between year 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 (see the sources of information breakdown in Fig. 1.)

About 30 thousand documents related to 35 aircraft types were reviewed to identify approximately 5,300 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 2,000 damage records were made on local fleet aircraft types (Ilyushin, Antonov, Tupolev and Yakovlev) and about 3,300 records on Boeing aircraft used by local operators. The operating time of the considered fleet resembled about 4 m flight cycles (F.C.) and 10 m flight hours (F.H.)

More than 80% of damages were related to errors during ground handling: falling baggage, dropped tools, collisions with airfield infrastructure and ground service vehicles. The ground hail, wind gusts and snow/sand storms caused about 10% of damage. Other 10% of damage sources were foreign objects impacts: runway debris, uncontained rotor burst, bird strike and tire explosion[12].

The types of damages were classified according to the breakdown shown in Fig. 2. The dent appeared to be the most frequent type (more than 50%), with depth sizes ranging from 0.1 mm to 50 mm. Out of this breakdown for the purposes of current study, only the wing skin surface dents (Fig. 3) were taken into consideration since this type of damage provides possibility to recover impact energy from dent geometry that is required for damage tolerance analysis.
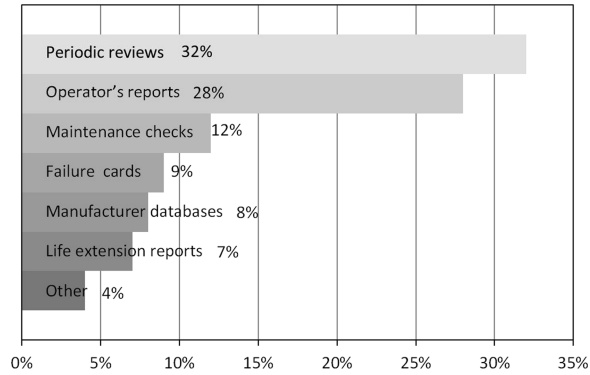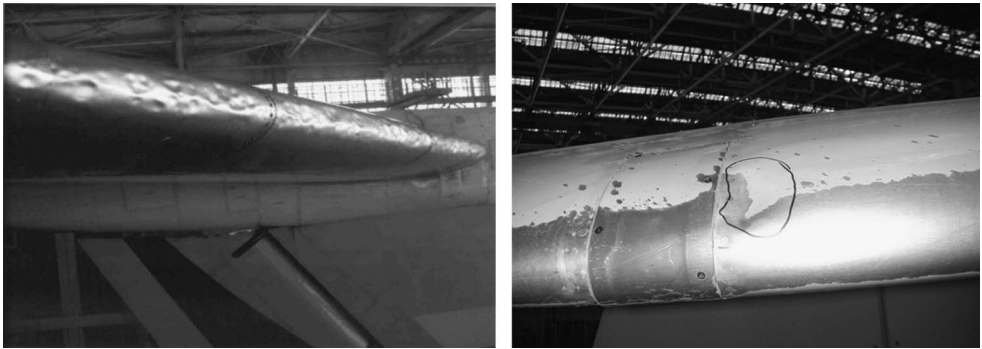
Figure 2. Breakdown of damage type.

Figure 3. Wing skin metal dent examples.

2.3 Probabilistic model

In order to evaluate the probability of accidental in-service impact into the 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[13]:

$$f(t) = \lambda e^{-\lambda t}, \qquad \qquad \dots (1)$$

and the damage probability function P_D can be expressed as

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

Table 1
Average flight time until damage and damage intensity for different aircraft types

i	Aircraft type	Number of damage events, Ni	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	189,201	44554	524.10	123.42	1.91×10^{-3}	8.10×10^{-3}
2.	Antonov 26	50	333,137	173199	6662.74	3463.98	1.50×10^{-4}	2.89×10^{-4}
3.	Antonov 24	142	1,084,536	561,827	7,637.58	3,956.53	1.31×10^{-4}	2.53×10^{-4}
4.	Antonov 12	98	198,609	60,342	2,026.62	615.73	4.93×10^{-4}	1.62×10^{-3}
5.	Yakovlev 42	258	669,690	302,361	2,595.70	1,171.94	3.85×10^{-4}	8.53×10^{-4}
6.	Yakovlev 40	75	669,690	302,361	8,929.20	4,031.48	1.12×10^{-4}	2.48×10^{-4}
7.	Tupolev 204/214	40	397,525	99,116	9,938.13	2,477.90	1.01×10^{-4}	4.04×10^{-4}
8.	Tupolev 154	554	3,140,130	1,290,513	5,668.11	2,329.45	1.76×10^{-4}	4.29×10^{-4}
9.	Tupolev 134	153	1,535,327	804,717	10,034.82	5,259.59	9.96×10^{-5}	1.90×10^{-4}
10.	Ilyushin 96	120	299,165	49,851	2,493.04	415.42	4.01×10^{-4}	2.41×10^{-3}
11.	Ilyushin 86	98	417,542	129,373	4,260.63	1,320.13	2.35×10^{-4}	7.58×10^{-4}
12.	Ilyushin 62	75	357,900	73,637	4,772.00	981.83	2.10×10^{-4}	1.02×10^{-3}
13.	Boeing 767-200	360	20,784	6,273	57.57	17.38	1.74×10^{-2}	5.75×10^{-2}
14.	Boeing 737-800	408	123,981	40,260	303.88	98.68	3.29×10^{-3}	1.01×10^{-2}
15.	Boeing 737-500	1,345	347,752	147,424	258.55	109.61	3.87×10^{-3}	9.12×10^{-3}
16.	Boeing 737-400	1,140	55,944	25,488	49.074	22.36	2.04×10^{-2}	4.47×10^{-2}
	Total	**5,277**	**9,840,913**	**4,111,296**				
	Average				**1,842.87**	**769.91**	**5.43 × 10^{-4}**	**1.30 × 10^{-3}**

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

$$\lambda = 1 / T \qquad \qquad \ldots(3)$$

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

$$\overline{\lambda}_i = N_i / T_{\Sigma i} \qquad \qquad \ldots(4)$$

Here, N_i is the total number of registered damage events for all aircraft 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.

It follows from Table 1 that the damage events intensity per F.H. averaged over the full data set makes

$$\overline{\lambda} = \sum_{i=1}^{n} N_i / \sum_{i=1}^{n} T_{\Sigma i} = 5.43 \times 10^{-4} \qquad \qquad \ldots(5)$$

For the qualitative characterisation 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 2.

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 [14]). In the current case, it means that in order to evaluate the conditional probability of the impact into given zone of the wing element $\overline{p}_z^n$, one should take into account the following probabilities:

- averaged probability $\overline{p}_e$ that the wing element is damaged given that the airframe damage occurred;
- averaged probability $\overline{p}_{\text{dent}}$ 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

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

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

Here, n_e is the number of wing damage events, N_{Σ} is the total number of damage events, n_{dent} is the 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 and 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 $\overline{p}_{zn}^n$ is the $\overline{p}_z^n$ normalised per unit.

For the further analysis, in order to establish the realistic impact energy level and compare it to the similar estimations made by other authors, it is necessary, in accordance with

Table 2
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
	Sum of probabilities			**0.2907**	**0.9999**

Rouchon model[8], to determine the probability of impact into wing. The superposition theorem for homogeneous processes[15] gives for wing damage events intensity $\bar{\lambda}_{\text{wing}} = \bar{\lambda} \cdot \sum_{n=1}^{N_z = 34} \bar{p}_z^n$. Then the conditional probability of whole wing structure impact damage,
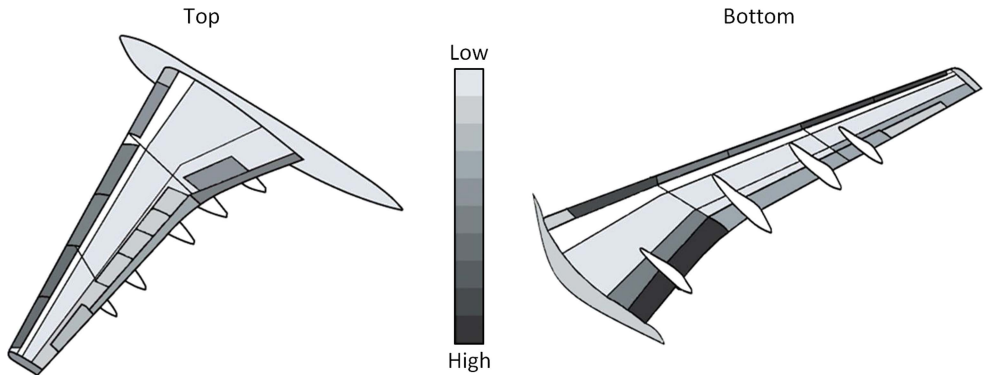
Figure 4. Wing relative damageability $\overline{p}_{zn}^n$.

derived from Equation (2) for $t = 1$ *F.H.* and for the sum of $\overline{p}_z^n$ presented in Table 2 becomes

$$P_{impact} = (1 - \exp(-\overline{\lambda}_{wing})) = (1 - \exp(-\overline{\lambda} \cdot 0.2097)) \cong 10^{-4} \qquad \dots(8)$$

The distribution of $\overline{p}_{zn}^n$ 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. In Fig. 4, one can see the qualitative distribution of impact intensity over the top and bottom surfaces of the generic wing.

It follows from Fig. 4 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.

Those observations and the impact distribution data presented in Table 2 and in Fig. 4 were obtained on aircraft types of different airframe configuration, see Table 1. Nevertheless, the facts that wing of generic transport category aircraft possesses a certain number of standard elements, (wingbox, high-lift device, ailerons and air brakes) and that the commercial fleet nowadays goes through very similar field maintenance procedures lead to the assumption that the generic accidental impact scenarios needed on the stage of preliminary design can successfully be taken from the above analysis. The evaluation of impact threats and corresponding structural damage related to the specific aircraft type should be done on the late development stage addressing the detailed design scheme and expected operating conditions.

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[16] 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 that 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.
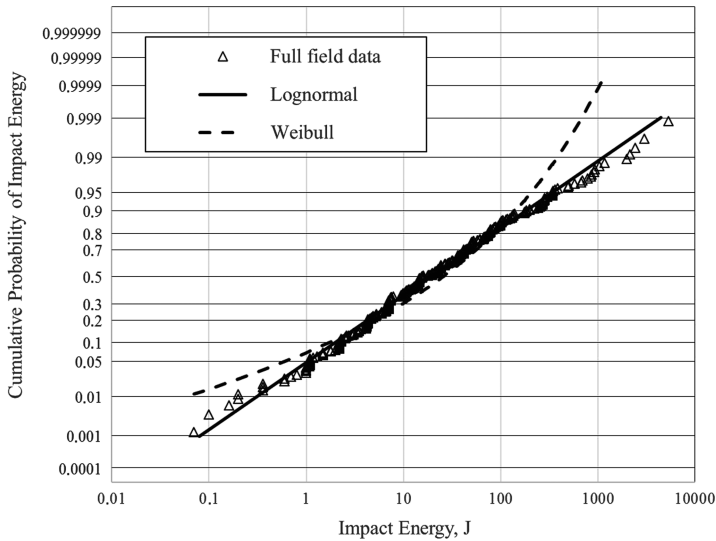
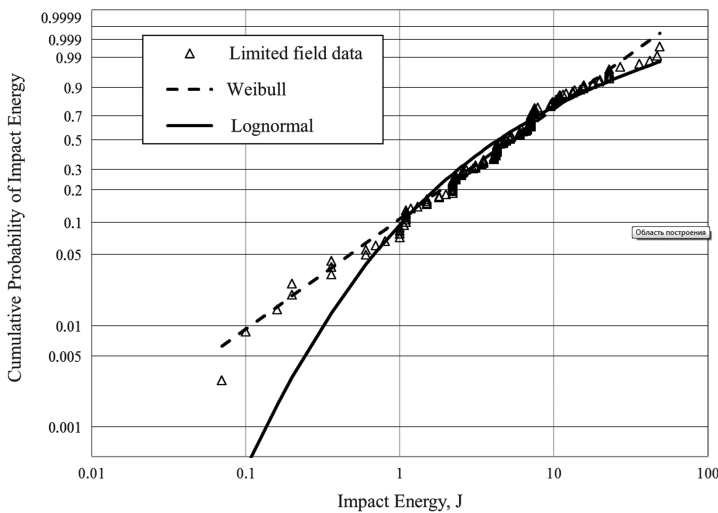Figure 5. Cumulative impact energy probability for full data sample (Lognormal scale).

Figure 6. Cumulative impact energy probability for limited data sample (Weibull scale).

Unlike the Northrop and MCAir survey analysed 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 in (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 in Figs 5 and 6.

The empirical distribution of full data sample (Fig. 5) is very close to a logarithmically linear function. The hypothesis, that impact energies are distributed according to

Table 3
R^2 regression errors for Lognormal and Weibull distributions

Data sample	R^2 criterion	
	Lognormal	Weibull
Full	0.99	0.93
Limited	0.98	0.98

logarithmically normal law, was checked by $n\omega^2$ criterion for two unknowns[17]. 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 $\alpha = 0.05$[18]. Thus, the 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 does not agree with the empirical distribution (Fig. 5).

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[19]. It follows from Fig. 6 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.

The R-squared regression errors for the fitted distributions are given in Table 3.

2.5 Impact energy characterisation for damage tolerance analysis

Although it is reasonable to assume that for the determination of realistic impact energy level the use of limited data sample is more adequate than the use of full data sample which includes such unrealistic events as serious collision with airfield buildings, equipment, GSE and other aircraft, 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, (for their impact sensitivity and brittle behavior). 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 the Rouchon model[9] and the approach presented in Handbook[20], 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 $P_E(E)$:

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

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 $P_{\text{impact}} = 10^{-4}$ derived above from local field data, see Equation (8), and the second one $P_{\text{impact}} = 10^{-3}$ taken from Gary [3] and Airbus [4] studies) are shown on Figs 7 and 8. The full and limited data sample distribution functions were approximated, respectively, by Lognormal and Weibull laws.
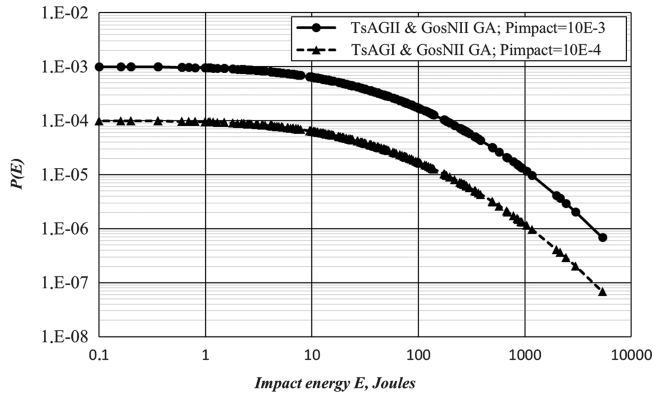
Figure 7. Probability to encounter in operation an impact with an energy exceeding E for full data sample (Lognormal law).
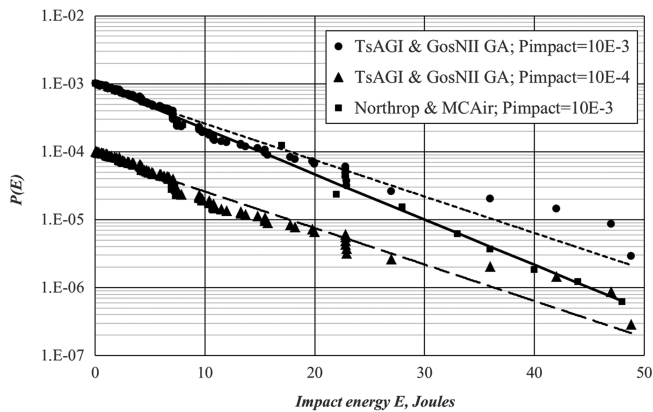

Figure 8. Probability to encounter in operation an impact with an energy exceeding E for limited data sample (Weibull law).

Table 4
'Maximum' and 'Realistic' 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}
$E_{maximum}$ $(P = 10^{-9})$	n.a.	90 J	110 J	100 J	n.a.	n.a.
$E_{realistic}$ $(P = 10^{-5})$	136 J	35 J	36 J	18 J	180 J	1140 J

According to the advanced non-conservative damage tolerance methodology presented in Refs 4,9,18 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 $P(E_{\text{realistic}}) = 10^{-5}$ *F.H.* The 'severe' or 'maximum possible' energy level may be determined by criterion of almost improbable event, namely 10^{-9}: $P(E_{\text{maximum}}) = 10^{-9}$ F.H.

Using the relationships in Figs 7 and 8, the energy levels corresponding to those probabilities were determined, and the summary results are presented in Table 4.

'*Unrealistic*' *scenarios* (Fig. 7): 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 ($P_{\text{impact}} = 10^{-3}$), 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 10 times per service life.

'*Realistic*' *scenarios* (Fig. 8): 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 $P_{\text{impact}} = 10^{-3}$ makes $E_{\text{realistic}} = 36$ J. This figure matches Airbus threshold value $E_{\text{realistic}} = 35$ 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 in Fig. 8 confirm that impact of 136 J accepted as a threshold value in Boeing damage tolerance methodology[21] can be considered as a remote event.

3.0 DISCUSSION

On the one hand, improbable events may not be considered as applicable data for the evaluation of 'realistic' energy threshold and thus the estimations made in Table 3 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[22,23] which recently became a matter of concern for FAA[24]. 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 minimise errors in ground handling. It is also assumed that airfield personnel do not intentionally damage aircraft. 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 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[15]) and applicable probabilistic distribution (Weibull versus Lognormal).

A few words should be said about the inspection methods suitable for the detection of the impact damages described in the above analysis. Despite the considerable advances in non-destructive inspection (NDI) techniques, the visual inspection remains the basic method of airframe integrity control in operation. One of the reasons for that is potential increase of operation costs related to introduction of complicated NDI methods which may bring down the competitiveness of composite aircraft compared to the metal ones. The general principle is as follows: if any signatures of disintegrity are revealed during visual inspection, then an in-depth analysis of material in this zone has to be performed using special instruments. The several decades of local commercial fleet operating history monitoring led to the conclusion that ultrasonic, thermography and low frequency acoustic methods (e.g. tap-testing) are the most efficient for the damage detection in composite structures. The recent comparative study of those methods (with addition of radiography and eddy-current) demonstrated that for the detection of impact-caused delamination in empennage stiffened composite panel, the ultrasonic technique is the most adequate and reliable[25].

4.0 CONCLUSIONS

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[4,9,20] to a large 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 received proper 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 Boeing[21] 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 an optimistic approach. Based on this study, the damage tolerance parameters for composite wing of commercial aircraft can be reliably substantiated, the maintenance program can be optimised and the damage inspection methods can be improved.

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