Composites Part B 176 (2019) 107258

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Experimental evaluation of surface damage relaxation effect in carbon-fiber reinforced epoxy panels impacted into stringer

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ARTICLE INFO

Keywords:
BVID
Damage tolerance
Relaxation
Moisture

ABSTRACT

Evaluation of the impact damage visual detectability threshold in composite structures requires not only determination of damage state right after the impact, but also at the actual moment of the visual inspection. Due to the specific features of aircraft maintenance programs the time between those two events may be considerable. During that time the damage size in the structure, subjected to operational and environmental factors, can be reduced (relaxed). To characterize the relaxation effect in typical aircraft stiffened panels, the long-term behavior of surface impact dents was investigated. It was demonstrated that among all the factors potentially reducing the dent depth, the combination of moisture and elevated temperature appears to be the critical case. Based on the results of the study the input data for damage tolerance analysis of commercial aircraft composite structures was obtained and recommendations on its applicability were formulated.

1. Introduction

Despite the considerable advances in non-destructive inspection (NDI) techniques the visual check 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 airplanes compare to the metal ones. Thus, the currently accepted damage tolerance philosophy fully relies on visual detectability; if any signatures of disintegrity are revealed during visual inspection, then an in-depth analysis has to be performed by NDI, otherwise structure is considered to be undamaged and capable to withstand any design load of flight spectrum.

In the frameworks of this approach the Barely Visible Impact Damage (BVID) is considered as fundamental damage tolerance criterion. To evaluate how service and human factors affect this criterion, many studies were performed by aircraft manufacturers. Among the available results the FAA-coordinated studies [1,2], two comprehensive European projects [3,4] and local research program [5] can be mentioned. And until now the models of the composite structure behavior after low-velocity impact [6,7] as well as BVID detection techniques [8–10] remain in the focus of aircraft industry.

The effect of composite damage size reduction in time (or damage "relaxation") may significantly affect the visual detectability threshold. It may lead to the situation, when VID (visible impact damage), detectable immediately after the impact, becomes undetectable over time, so this hazard should be thoroughly addressed.

Early studies of surface dents relaxation in composites date back to the 90s of the 20th century [11–13]. Komorowski [11] first investigated the relaxation phenomenon on coupons. The obtained results, which were subsequently confirmed by Thomas [12], proved that in some cases the initial damage size, (namely dent depth), obtained just after impact is three times greater than at the end of life. It was also assumed that the dent depth can decrease over time due to long-terms effects as a result of fatigue and humidity. The study of time-dependent relaxation was continued by Komorowski [8] on composite panels stiffened with Ω-stringers impacted into skin: the dent size reduction up to 40% from initial level was observed and this generally confirmed the earlier results on coupons [13].

Recommendations of [11–13] were incorporated by Aerospatiale [14], Boeing [15] and Airbus [16] into composite airframe damage tolerance methodology, which prescribes to account for the relaxation

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https://doi.org/10.1016/j.compositesb.2019.107258
Received 6 April 2019; Received in revised form 1 July 2019; Accepted 8 August 2019
Available online 8 August 2019
1359-8368/

effect. In Airbus report [15] the generic picture of impact damage relaxation behavior in normal and hot-wet conditions as well as under cyclic loads of the flight spectrum may be found. It was shown, that for considered materials and design solutions, the thermal aging became a critical factor that envelopes the effect of all others, but no quantitative characterization of this mechanism was provided.

Though the above results proved that the relaxation in composite structures can critically affect the aircraft safety, there is no much dedicated publications in open literature. The data in previous studies was limited by consideration of short-term relaxation in flat laminates [13] and qualitative description of moisture effect [15]. In the current paper it was attempted to cover other topics important for damage tolerance analysis, namely to address the response of stiffened panel, impacted into stringer, with subsequent long-term behavior of the damage, propose physical grounds for acting mechanism of hot-wet "recovery" and calculate the relaxation-related safety factors. The knowledge of surface damage relaxation basic laws in composite structures can improve the reliability of airframe visual inspection procedures, which are currently based on criteria [1–5], proposed earlier by manufacturers and researchers in NDI area.

2. Material and methods

The investigation of impact damage relaxation phenomenon in composite structures became a follow-up of the experimental program, focused on visual detectability threshold evaluation, the methodology and main results of which are presented in [5].

The term "relaxation" is used here to describe the spring-back effect of the surface damage in composite structure caused by low velocity impact. Under damage size the depth measured by contact dial gauge method [17] is meant. This method was compared to the techniques of digital image correlation (DIC) and laser profilometry and showed the best accuracy for the panel geometry utilized for the study.

For experiment the two carbon fiber reinforced panels typical for empennage structure with size of 320 × 320 × 3.2 mm reinforced with three T-shaped stringers were taken, (see Fig. 1). The panels were fabricated from Hexcel glass and carbon epoxy prepregs: HexPly M21/45%/120 (superscript "g") and HexPly M21/34%/UD194/IMA (superscript "c") respectively, see Table 1. The least material was also used for the fabrication of stringer "noodle" area. The 9-plies layup of skin and stringer was similar with one ply of glass fiber on external surface: $[0°g, +45°c, -45°c, 0°c, 90°c, 0°c, 0°c, +45°c, -45°c]$. The physical properties of prepeg used for stringer panel fabrication are presented in Table 2.

After painting at aircraft production facility, the panels were impacted by 25 mm spherical indenter on CEAST 9350 Drop Tower Impact System into 9 locations under the stringer, (see Fig. 2). Resulting dent sizes fell into the 0.21–0.88 mm interval.

The dent size measurements were carried out for 170 days in total. At the first stage the relaxation was observed in room temperature conditions. At the second stage of experiment the same panels were put into climatic chambers to evaluate the environmental effects.

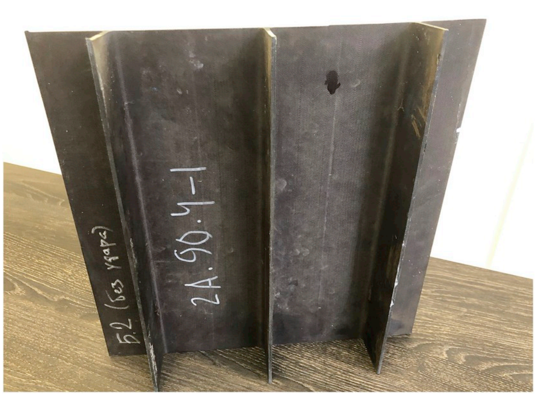

Fig. 1. Experimental panel.

Table 1
The stacking sequence.

Element	Plies	Stacking sequence
Skin	9	$(0°g, \pm45°c, 0°c, 90°c, 0°c, 0°c, \pm45^c)_S$
Stringer	9	$(0°g, \pm45°c, 0°c, 90°c, 0°c, 0°c, \pm45^c)_S$

Table 2
Physical properties of prepeg used for stringer panel fabrication.

Physical Property	Units	M21/45%/120	M21/34%/UD194/IMA
Fiber		E-Glass	IMA
Weave/UD		4HS	UD
Fiber mass	g/m^2	105	194
Nominal prepreg mass	g/m^2	193	294
Nominal cured ply thickness	mm	0.106	0.184
Nominal fiber volume	%	38.4	59.2
Resin density	g/cm^3	1.28	
Fiber density	g/cm^3	2.56	1.78
Nominal laminate density	g/cm^3	1.77	1.58

3. Results and discussion

3.1. Stringer panel structural response

The damage initiation and propagation mechanism, which took place in the impacted structure, is shown of Fig. 3. The impact test configuration was arranged in the way to simulate the most severe damage with minimum visual detectability and maximum internal failures. During impact test the panel rested on stringers and the energy was absorbed through the compression forces directed towards the stringer center axis (Fig. 3 a). Acting as a wedge, the T-stringer "noodle" caused high tensile stresses in the lowest ply of skin-stringer radius, which has led to clearly visible delamination, (Fig. 3 b).

Due to the matrix driven energy absorption mechanism the fiber-related failure modes didn't take place on the surface of the panel: the external signatures of impact damage, that caused the abovementioned significant delamination in radius area, appeared to be barely visible, (Fig. 3 c). The impact over stringer was selected as a representative case for the reasons of conservatism: the degree of relaxation in the dent inflicted over stringer may be an order of magnitude higher than the same effect in the dent inflicted into skin, because flat panels are more flexible and absorb energy through bending, causing minor dents.

3.2. Relaxation in room temperature conditions

The quantitative characterization of the relaxation process was made through the value of relative residual dent depth $R = \delta_R/\delta_{init}$, where δ_{init} and δ_R are initial and current dent sizes respectively.

The dent behavior in RT (room temperature) conditions for few hours after the impact was characterized through DIC measurements, see Fig. 4. All further measurements, which took place during next 97 days, while panels were stored in the lab with temperature range 21°C–25 °C and air humidity 40%–50%, were performed by contact method. The dents were measured once in a day during the period "day 1- day 10"; every 3 days during the period "day 11 - day 20" and then once in a week. It was observed that during first days the dent reduction process stabilized, however, the further tests demonstrated, that the relaxation continued.

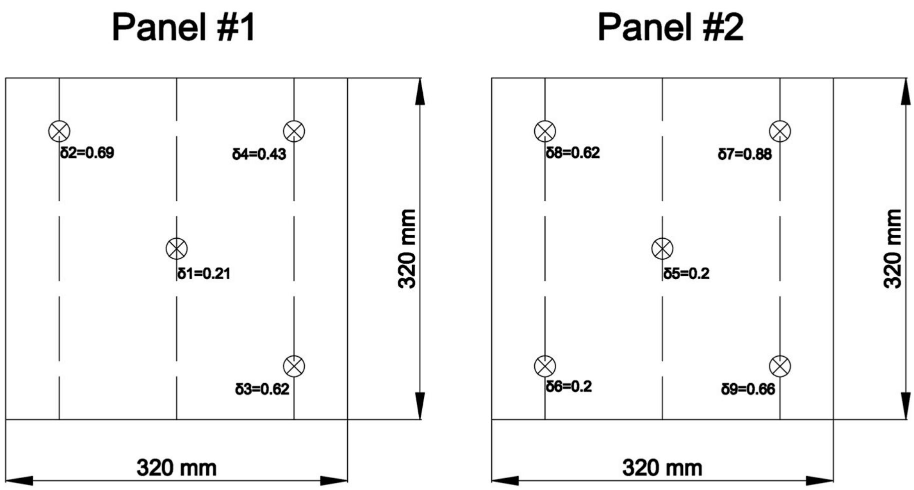

Fig. 2. Impact locations.

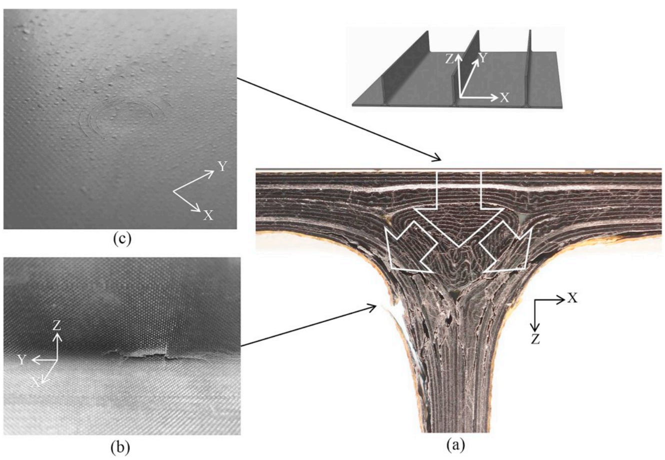

Fig. 3. a) Cross section of damaged panel, b) Visible delam in radius area, c) Dent caused by 26 J.

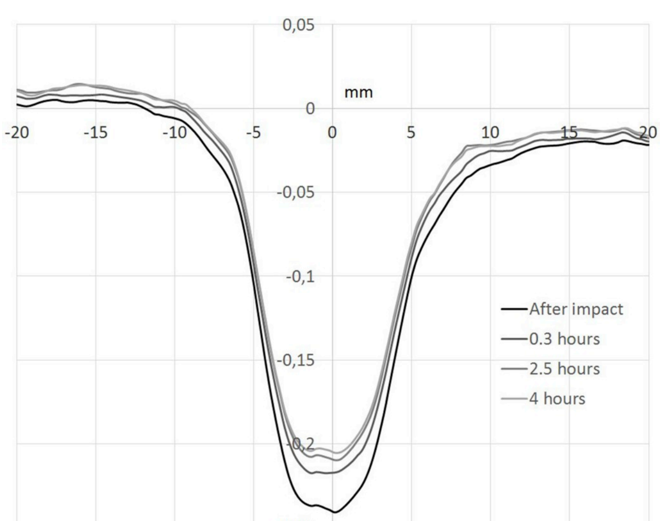

Fig. 4. Relaxation immediately after impact.

In order to identify the basic laws of this process, it was first checked, whether the mean value of relaxation can be accepted as representative parameter or, in other words, whether relaxation depends on the damage size. For this purpose, data distribution was tested for normality and linear regression "residual vs. initial size of the dent" was calculated for 9 dents after 97 days. For comparison the legacy data of study [5] was revealed and the 65 dents with sizes 0.03–1.68 mm, inflicted on the identical three-stringer panels by the same experimental methodology [5], were remeasured after 1.5 year of storage in the lab with room temperature conditions. It appeared, that fitted curves "9 dents after 97 days", (red line on Fig. 5), and "65 dents after 1.5 year", (blue line on Fig. 5), exhibit very low regression errors and possess almost equal slopes, namely $d\delta_{RT}/d\delta_{init}(97\ days) = 0.7775$ and $d\delta_{RT}/d\delta_{init}(1.5\ year) = 0.7765$. This lead to the conclusion, that relaxation in considered conditions does not depend on the damage size. If so, the data can be combined and relaxation mean value $\bar{R}_{RT}$ can be used for analysis. It follows from Fig. 6, showing $\bar{R}_{RT}(t)$ function with error bars, that measured data fits well logarithmic approximation and this function can be accepted as relevant law for the considered process.

In Table 3 the mean relaxation values are presented. According to this data, the short term relaxation, characterized by abrupt size reduction can be estimated as $\bar{R}_{RTst} \approx 0.87$, (Table 3, day 3). The long term relaxation, calculated by the end of the test through the mean value $\bar{R}_{RTlt} = 0.79$ (Table 3, day 97), is slightly greater, than slopes $d\delta_{RT}/d\delta_{init} = 0.78$ on Fig. 5, calculated by least square method, so for further damage tolerance consideration it is proposed to use the least as the

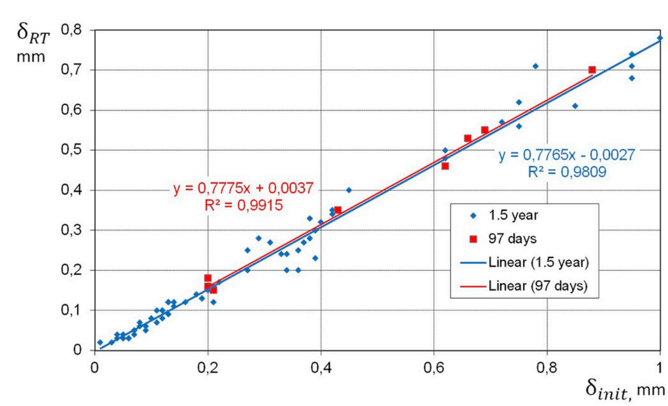

Fig. 5. Initial depth vs. residual depth after 1.5 year and after 97 days in RT.

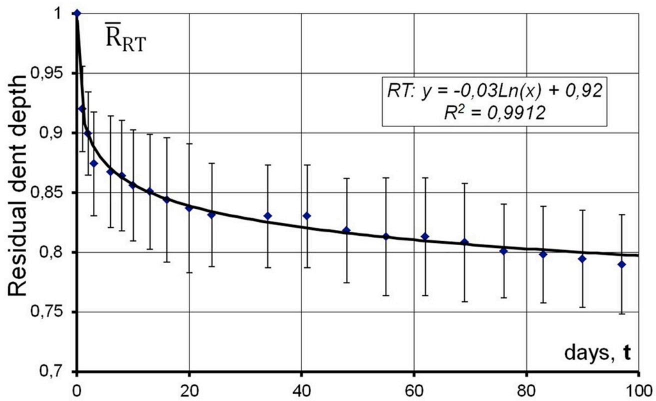

Fig. 6. Long-term relaxation.

Table 3
Relaxation mean values in time, 97 days in RT followed by 73 days in ETD/ETW.

Storage in RT conditions		Conditioning in ETD/ETW climatic cambers				
T, days	$\bar{R}_{RT}$	T, days (in chamber)	$\bar{R}_{ETD}$	$\bar{R}_{RT+ETD}$	$\bar{R}_{ETW}$	$\bar{R}_{RT+ETW}$
0	1	97 (0)	1	0.79	1	0.79
1	0.92	99 (2)	0.89	0.70	0.67	0.53
2	0.90	103 (6)	0.88	0.70	0.64	0.51
3	0.87	106 (9)	0.87	0.69	0.63	0.50
6	0.87	110 (13)	0.85	0.68	0.63	0.50
8	0.86	113 (16)	0.83	0.66	0.63	0.50
10	0.86	118 (21)	0.83	0.66	0.62	0.49
13	0.85	121 (24)	0.83	0.66	0.57	0.45
16	0.84	146 (49)	0.83	0.66	0.53	0.42
20	0.84	156 (59)	0.82	0.65	0.50	0.40
24	0.83	163 (66)	0.82	0.65	0.50	0.40
34	0.83	170 (73)	0.81	0.64	0.49	0.39
41	0.83					
48	0.82					
55	0.81					
62	0.81					
69	0.81					
76	0.80					
83	0.80					
90	0.79					
97	0.79					

conservative approximation.

The observations made lead to conclusion that two different mechanisms are responsible for short-term and long-term relaxation effects. The short-term effect, taking place right after the impact, may be explained by the viscous-elastic response of the structure in assumption of standard linear solid model, which is simple combination of springs and dashpots, and well-studied in literature [18,19]. The long-term effect is more complex and few assumptions should be made for its characterization. This mechanism may have three main sources: visco-elastic response [20], plasticity deformation [20,21] and material damage growth [22]. It is hard to distinguish what part of the dent size caused by particular mechanical effect. The plasticity deformations are irreversible; damage deformations modify elastic properties and can contribute to the dent size but they are reversible. Thus, there are only two opportunities to explain such a long delay in spring back of the dent depth. The first one is essentially high delay time for low frequencies in elastic viscosity of the material and the second one – this material feature of high delay time has been developed during damage growth. The second assumption can be explained by the development of small micro cracks, which cause additional internal friction that delays the spring back movement of the matrix material. In addition, the idea of changed mechanical characteristics of damaged material can be backed by self-healing effect [23], which reduces the number of small cracks in polymer or its area during time, on macro level this causes increase of the stiffness of the damaged material. It is very common situation, when the temperature increase acts as a trigger for self-healing process in the polymer. Wool in [24] showed that the fracture toughness K_I is proportional to $t^{1/4}$, where t is the contact time of closed crack surfaces of the polymer material. This dependence of $t^{1/4}$ qualitatively resembles the chart of long-term relaxation shown on Fig. 6. Nevertheless, the effect gives argues for increase of the part of viscous contribution of the material deformation instead of plasticity one during dynamic loading.

3.3. Relaxation in hot-wet conditions

At the second stage of the study, the same two panels, previously used for RT relaxation test, were placed into the climatic chambers ASC DISCOVERY DY1600 for other 73 days. In first chamber the panel was dried at a temperature of 70 °C and a humidity of 10%, (this mode below denoted as "ETD" – elevated temperature dry), in the second chamber the panel was saturated at a temperature of 80 °C and relative humidity of 90–95%, (this mode below denoted as "ETW" – elevated temperature wet). The drying and moisture saturation processes were controlled by traveler specimens – halves of the investigated panels with size 150 × 300 mm. Each three days the specimens were taken out of the chamber and transported in polyethylene bag to the workplace to measure dent size and weight; the procedure took not more than 5 min.

The relative change of mass in ETD traveler made more than 0.6% by the end of the test, Fig. 7. Because the weight gain of typical airframe composites is on the order of 1% [25], it can be assumed that by the start of the test the specimens were close to maximum moisture content.

The $R(t)$ charts for ETD and ETW panels are shown on Fig. 8. In both cases, as well as in RT test, the abrupt size reduction during first two or three days was observed. The corresponding values of short-term relaxation can be estimated as $\bar{R}_{ETDst} \approx 0.89$ and $\bar{R}_{ETWst} \approx 0.67$, (Table 3, day 99). In a while, both relaxation process exhibited stabilization, but at considerably different levels. The aggregated long term relaxation for 170 day test, (which is a sum of dent size reduction in RT mode during 97 days and in ETD/ETW modes during next 73 days), made $\bar{R}_{RT+ETDlt} = 0.64$ and $\bar{R}_{RT+ETWlt} = 0.39$, (see Table 3, day 170). The relaxation behavior of two panels throughout the 170 day is shown on Fig. 9, and significant effect of ETW conditions is very consistent with Airbus observations, [15]. The testing summary, including actual impact energies and evolution of damage size throughout the test for all 9 dents, is presented in Table 4.

The effect of abrupt dent size reduction in both panels placed into elevated temperature after long-time exposure in RT conditions mean that similar relaxation mechanism takes place in both cases. This phenomenon is probably related to moisture evaporation from the fiber-matrix interface caused by hot environment. One mode differs from

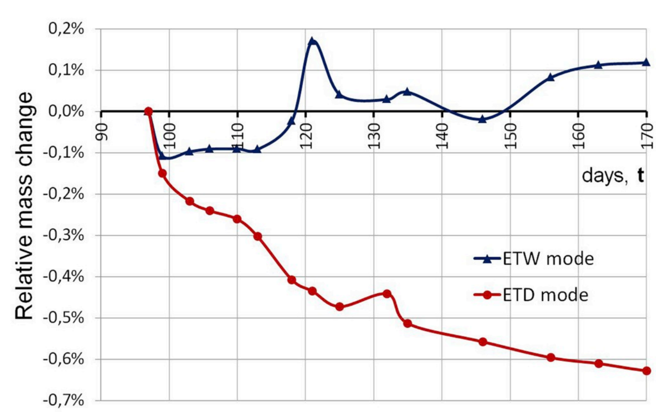

Fig. 7. Comparison of mass change in traveler specimens.

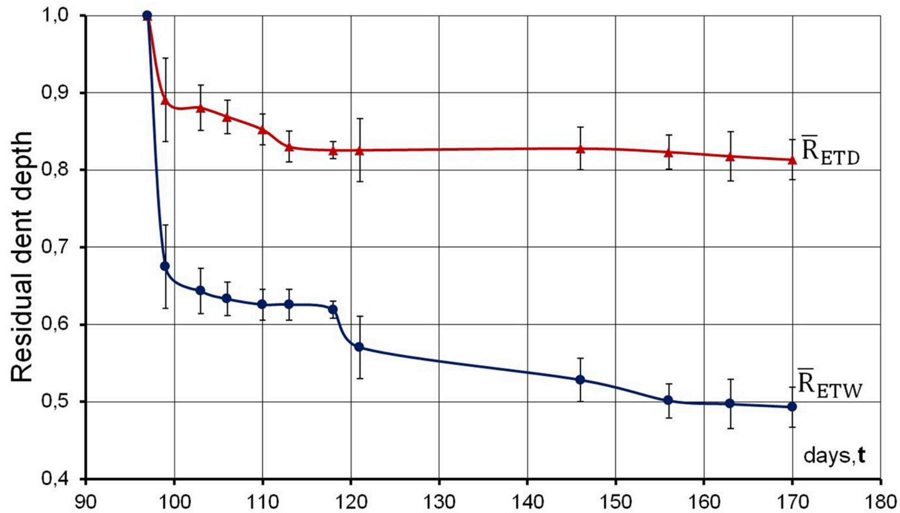

Fig. 8. Relaxation in ETD and ETW modes.

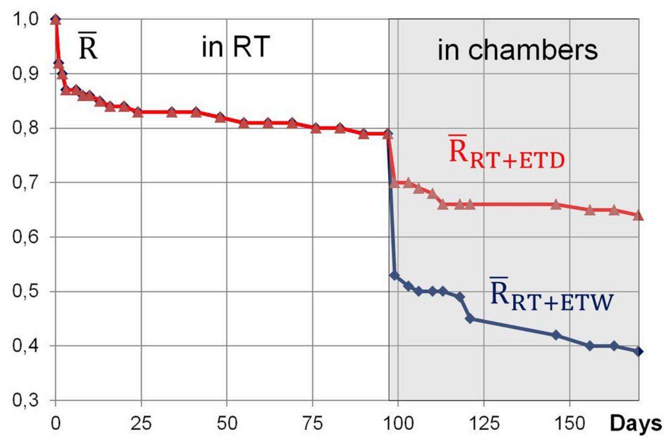

Fig. 9. Aggregated relaxation (mean values).

Table 4
Impact energies and evolution of dent sizes.

Dent №	Energy, J	δ_{init}, mm	δ_{RT}, mm	δ_{RT+ETD}, mm	δ_{RT+ETW}, mm
		day 0	day 97	day 170	
1	26	0.21	0.15	0.13	n/a
2	66	0.69	0.55	0.43	
3	67	0.62	0.46	0.37	
4	58	0.43	0.35	0.28	
5	26	0.20	0.16	n/a	0.08
6	26	0.20	0.18		0.09
7	67	0.88	0.70		0.35
8	59	0.62	0.46		0.21
9	60	0.66	0.53		0.27

another by the amount of moisture available for absorption, thus in ETD mode it comes to the equilibrium state earlier than in ETW mode.

The physical nature of the relaxation process taking place in hot-wet environment may be illustrated by the following example. Two laws were tested for ETW data fit: exponential function $R(t) = R_\infty + \Delta R \cdot exp(-t/\beta)$ and power function $R(t) = R_\infty + \Delta R/(1+t)^\alpha$, (here R_∞ is the fully irreversible depth; ΔR is the reversible part of dent size, but not in phase with stresses; α, β - model parameters, t – time). It was found, that power function fits better with mean squared error σ two times less than in case of exponential law, see Fig. 10. The fractional index of power function leads to the assumption that physically the damage relaxation process under hot-wet conditions in the considered case (epoxy matrix, impact into stringer, severe internal delaminations) exhibit the features of the diffusion. The same physical mechanism following Fick's Law acts for moisture gain in solid non-damaged laminates [26].

After exposure in climatic chambers the panels were taken out and stored approximately for the year in the lab with the environment close to RT conditions and moisture level varying seasonally from 20% to 80%. The year after, dent sizes of ETW panel were reevaluated with the same contact method and it was found, that all of them remained on exactly the same level accurate to measurement error. Thus, the moisture diffusion-driven recovery of the composite surface dent may be characterized as irreversible process, contributing much into internal damage concealment.

In present study the phenomenon was investigated on specimens, conditioned in a quasi-static manner and without loads, which is in contrast to the real world scenario, where airframe is subjected to ground-air-ground cycles and loaded by aerodynamic forces. The studies, focused on the effect of these service factors, are planned on the next phase. On the current stage it can be mentioned, that Airbus [15] didn't notice any visible input of fatigue loads into relaxation, probably because of the low allowable stresses in the structure, designed according to "no-growth" approach. As for thermal cycling, it was also mentioned in [15] and confirmed on coupons in [27], that temperatures below freezing point have weak effect on composite damage size

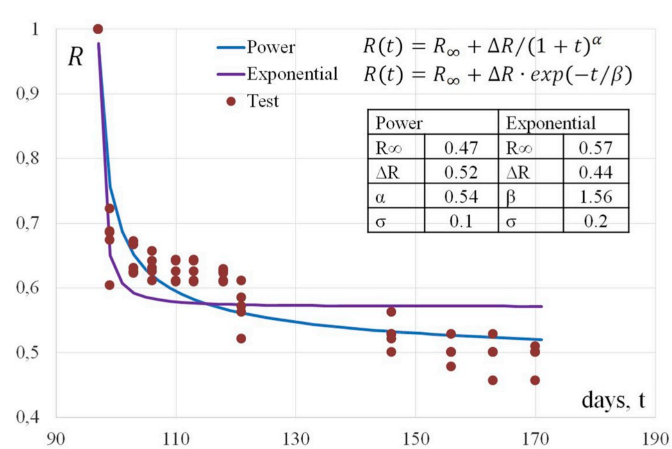

Fig. 10. ETW data fit.

reduction.

The basic laws of dent size evolution, identified above, provide possibility to simulate the worst-case scenario by condition of relaxation. Since hot-wet exposure appears to be the critical issue, the worst case scenario will be receiving of BVID in first flight after completion of heavy maintenance check by the aircraft, having domestic hub in humid continental climate. This scenario may cause long-term period of service, (i.e. period, comparable with operation limits, established in flight cycles or flight hours), of the structure, containing hidden internal damage, grown beyond the size, proved during certification.

3.4. Input data for fatigue and damage tolerance evaluation

The modern damage tolerance approach is based on the five category classification of the damage, potentially expected in operation. Damage is classified depending on the operating time needed for its reliable detection within the accepted aircraft maintenance program. Substantiation for Category 1 and Category 2 damage includes demonstration of ultimate load capability after the fatigue life for the structure with BVID and limit load capability after the interval, needed for reliable detection of the damage, for the structure with VID respectively [28]. This is usually done in full scale fatigue test, (FSFT). Parameters of impacts to inflict on FSFT article may be chosen conservatively [14] or according to the results of field data analysis [15,29]. To mitigate the above-mentioned risk to exceed in operation the allowable damage limits, those impacts should be inflicted with account for relaxation, i.e. the dent size should be corrected depending on R: $\delta_{eff} = \delta_{cert}/R_{eff}$, were δ_{eff} is effective dent size, δ_{cert} is the "certification" damage size, R_{eff} is the relaxation factor, specific for the given element. To obtain the dents of larger size, the higher impact energies E_{eff} should be applied, see example of calibrating function "impact energy vs. damage size" on Fig. 11.

In the analysis of the present study, two mechanisms and two environments were considered for relaxation phenomenon: short-term and long-term processes in RT and ETD/ETW conditions. Their possible combinations are presented in Table 5, and the following interpretation of R_{eff} dependence from service and design issues may be proposed. Since the intervals between detailed visual inspections, assigned in the aircraft maintenance plan, may range from several days to several years for different parts of the airframe, the appropriate choice should be done between short-term and long-term cases depending on the specific maintenance schedule. For the selection of adequate margin by condition of environmental effect, two scenarios may be considered. Typically, the aircraft doesn't spend much time on the ground to heat up over 30°C–40 °C, not to mention, that long term hot-wet conditioning seems too conservative. Nevertheless, there are airframe elements, exposed to the sun and humidity, thus, according to the Airworthiness Standards, the most conservative combinations should be taken into account. The relaxation in RT conditions is more realistic and in some cases it may be appropriate for substantiation of internal composite elements, not exposed to sun and moisture. With this engineering approach, considering specific design aspects and expected operating conditions of the given structure, the adequate relaxation factor can be selected from Table 5. For deeper insight into process, the proposed laws of relaxation in RT and ETW modes, shown on Figs. 6 and 10 respectively, can be used.

It is worth mentioning, that proposed approach is valid not only for the elements, similar to thin flat stiffened panels, taken as representative specimens in the present study, but for other designs as well. For example, it can be applied for not very thick composite panels with slight curvature. The curved shell type structures may exhibit different mechanics of deformations; however, the measure for this difference can be formulated as the ratio of the dent depth to the curvature radius, which is usually essentially small for fuselage.

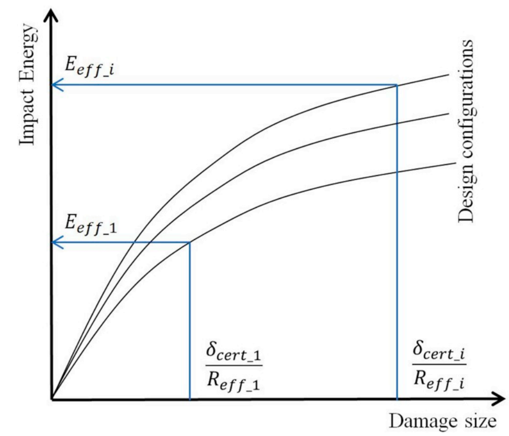

Fig. 11. Example of calibrating function "impact energy vs. and damage size".

Table 5
Proposed effective values of relaxation factor.

Scenario	R_{eff}	
	Short term	Long term
Realistic	$\bar{R}_{RTst} = 0.87$	$\bar{R}_{RTlt} = 0.78$
Conservative	$\bar{R}_{RTst}\cdot\bar{R}_{ETWst} = 0.56$	$\bar{R}_{ETWlt} = 0.39$

4. Conclusion

The long-term observations of impact dent size evolution in time under different environmental conditions have demonstrated that in stiffened carbon-epoxy panels the process of surface damage size reduction may continue for a long time. The wet aging at elevated temperatures in comparison with other considered factors has the most critical effect on relaxation. For a certain conservative combination of factors, for example, impact into stringer with minor visibility and major internal damage followed by exposure hot-wet conditions, the dent size may decrease almost twice for a relatively short period of time and almost three times, for a period, comparable with the intervals between heavy maintenance checks.

Thus, the design criteria for composite structures based on the visual detectability of potential damage may become non-conservative, (i.e not safe enough) without taking into account the phenomenon of relaxation. The results of current study provided the qualitative parameters of relaxation which should help to adequately characterize this effect.

More global challenge is improvement of composite airframe weight efficiency [30]. Existing design solutions of Boeing 787, Airbus 350, Airbus 220 and MC-21 are still "black aluminum" solutions with intentionally overestimated safety margins, allowing for many mistakes. The ignoring of relaxation phenomena for the structure with 900 J large damage capability [14] may not even be an issue. However, there is no doubt, that new-generation structures will require more thorough attitude and deeper insight into the immanent features of composite materials. Hopefully the current study will be useful on this way.

ACKNOWLEDGEMENTS

This study would not have been possible without the help of Russian aircraft design and manufacturing companies PJSC "Irkut" and JSC "Aerocomposit". The part of the study was supported by the Russian Foundation for Basic Research (Grant no. 18-31-20026).

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