On the monitoring and implications of growing damages caused by manufacturing defects in composite structures

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Abstract. Damage tolerance is a classical safety concept for the design of aircraft structures. Basically, this approach considers possible damages in the structure, predicts the damage growth under applied loading conditions and predicts the following decrease of the structural strength. As a fundamental result the damage tolerance approach yields the maximum inspection interval, which is the time a damage grows from a detectable to a critical level. The above formulation of the damage tolerance safety concept targets on metallic structures where the damage is typically a simple fatigue crack. Fiber-reinforced polymers show a much more complex damage behavior, such as delaminations in laminated composites. Moreover, progressive damage in composites is often initiated by manufacturing defects. The complex manufacturing processes for composite structures almost certainly yield parts with defects, e.g. pores in the matrix or undulations of fibers. From such defects growing damages may start after a certain time of operation.

The demand to simplify or even avoid the inspection of composite structures has therefore led to a comeback of the traditional safe-life safety concept. The aim of the so-called safe-life flaw tolerance concept is a structure that is capable of carrying the static loads during operation, despite significant damages and after a representative fatigue load spectrum. A structure with this property does not need to be inspected, respectively monitored at all during its service life. However, its load carrying capability is thereby not fully utilized.

This article presents the possible refinement of the state-of-the-art safe-life flaw tolerance concept for composite structures towards a damage tolerance approach considering also the influence of manufacturing defects on damage initiation and growth. Based on fundamental physical relations and experimental observations the challenges when developing damage growth and residual strength curves are discussed.

1. Introduction
Lightweight structures, such as aircrafts, spacecrafts, automobiles, wind energy plants, etc. are designed in line with safety concepts to optimally operate the structure within specified limits. The strength limits are given (i) by the static strength allowables, (ii) by the structural durability pertaining to fatigue and (iii) by the crash resistance referring to dynamic loads. Static strength includes the design against fracture, instability and detrimental deformation (e.g. not acceptable permanent deformation). Structural durability includes issues such as fatigue and damage initiation, damage growth and the residual strength of the damaged structure. This latter topic is the core of the damage tolerance concept.
The most advanced safety concepts for lightweight design can be found in civil aircraft engineering. Historically this development was often initiated by tragic accidents, followed by an immediate refinement of the certification specifications by the certification authorities in collaboration with the aircraft industry:

- The traditional safety concept is the safe-life approach, i.e. the design of a structure for a specific time (or for a number of events) in which there is a low probability that the strength degrades below the applied loading during operation.

- Particularly the accidents with the Comet 1 aircrafts showed that the pure safe-life concept is insufficient [1]. This simple safety concept may yield a design which has no load carrying capability at all if one structural member fails. The fail-safe concept introduced in 1956 requires that the structure retains a residual strength for a period of unrepaired use after failure or partial failure of a structural member. Accordingly, a fail-safe design is redundant and statically indeterminate.

- However, in 1977 the fail-safe concept failed [1]. A Boeing 707-300 lost its horizontal stabilizer in flight since cracks in the lug connections (which were designed redundantly) were not detected early enough. As a consequence the damage tolerance requirements were introduced in 1978. The major message of this safety concept is the acceptance that damages may always be present and need to be considered in design (until identification and repair). Figure 1 shows the classical picture illustrating this safety concept: The lower curve shows the increase of damage size due to applied loading conditions. The upper curve shows the according decrease of the structure’s strength. The structure would fail if this residual strength falls below the design load (the maximum load level expected during operation [2]) in which case the damage would reach its tolerable level. This critical damage level may called fault. On the one hand, within the inspection program the damage needs to be detected in advance. On the other hand, with a specific inspection method, e.g. ultrasonic testing, it is only possible to detect a damage of a specific size. For this method the corresponding inspection interval is the time a damage grows from the detectable level to a fault. If the structure is inspected in these intervals, no damage can develop into a fault. The decision for a rougher (but more convenient and cheaper) inspection method, e.g. only visual inspection, naturally leads to a shorter inspection interval.

- In principal the above safety concepts focus on metallic structures where the damage is typically a simple crack at the surface. In contrast composite structures made from fiber-reinforced polymers show a rather complex damage behavior, for example delaminations or intra-laminar damages which are difficult to detect without sophisticated Non-Destructive Testing methods. The demand to simplify the inspection of composite structures has led to a comeback of the safe-life concept. The target of the so-called safe-life flaw tolerance concept is a structure that is capable of carrying the static loads during operation, despite significant defects and damages and after a representative fatigue load spectrum. A structure of this kind does not need to be inspected at all during its service life. A thorough formulation of this concept can be found in the certification specification CS-29 for large rotorcrafts [3].

The latter approach is pragmatic, practical, safe, thoroughly formulated and thus fulfills the current demands of industry and certification authorities. Nevertheless, it does not yield an optimized lightweight structure as the damage tolerance concept would offer. It should therefore be an aim to find an appropriate damage tolerance approach for composite structures.

However, with composites an issue arises, which complicates the introduction of a damage tolerance design concept. The complex manufacturing processes for composite structures almost certainly yield parts with defects, e.g. pores in the polymer matrix or undulations of fibers. Such defects may initiate growing damages after a certain time of operation which of course need to be considered by a refined damage tolerance approach.
2. Implications of manufacturing defects on the damage tolerance approach

As long as the structure is not totally damaged, its remaining life time can be predicted by damage growth considerations. As a result damage tolerance diagrams as shown in figure 1 follow. The development of such graphs is state-of-the-art in modern aircraft design for metal structures [4]. There are consequently two thrusts of current research: (i) the enhancement of the damage tolerance concept to consider also structures made from laminated composites (away from the currently accepted safe-life flaw tolerance approach described in section 1), and (ii) the enhancement of this concept for structural parts with manufacturing defects to consider not only structural damages (which occur during handling or use of the structure, as e.g. cracks, dents, or delaminations) but also defects (which are direct results of the manufacturing process, as e.g. pores or undulations).

For the latter enhancement we propose to derive modified damage tolerance diagrams as depicted in figure 2: The upper curves show the decrease of the structure’s strength due to flaws, i.e. the initial reduction of the strength due to defects and the progressive degradation due to growing damages. These residual strength curves define the current allowable loading. Finding the upper curves requires methods of flaw assessment. The lower curves show the progress of damages, which are initiated by defects after a certain time of operation. These damage growth curves are derived from applied loading conditions. Finding the lower curves requires methods of flaw prognosis. The structure fails if its strength falls below the design load; a statistically determined maximum load expected in service and increased by deterministic safety factors (see [2]). The determination of the design load is thus a topic of safety requirements and legal regulations. If the decreasing strength of the structure reaches the threshold of the design load the damage reaches its tolerable level, i.e. it becomes a fault.

The idealized diagrams in figure 2 indicate that a small defect leads to a higher initial strength of the structure immediately after manufacturing which further leads to a higher maximum tolerable damage level during handling or use. The actual tolerable damage level within the structure’s design life depends on the project-defined design requirements and is
Figure 2. The effect of manufacturing defects on the concept of damage tolerance (cf. figure 1).

again a subject of safety requirements and legal regulations. For example, from the effects of the three manufacturing defects depicted in figure 2 one could draw the following conclusions:

- Defect 1 initiates damage 1 after the design life has passed. If no damage growth is allowed within the design life only such a defect level is acceptable.
- Defect 2 initiates damage 2. However, this damage does not develop into a fault within the design life. If damage growth is allowed defect 2 is therefore acceptable.
- Defect 3 initiates damage 3 which becomes a fault within the design life. This defect level is therefore not acceptable.
- Of course, there exists also a (low) defect level near a perfect structure which initiates no damage growth at all (in the sense of an endurance strength limit).

In this way design requirements yield assessment criteria to tolerate manufacturing defects. These criteria may then be listed in a concession catalog. However, developing such an extensive catalog can become rather complicated, as it must also cover the parallel occurrences of several different defects. Here a possible approach could be the introduction of a score system, assigning each defect a specific number of points. The structural part is then divided into zones within which a maximum number of points is allowed.

3. Stiffness degradation and residual strength of fiber-reinforced composites

Figures 1 and 2 hypothesize graphs on the progress of the residual strength if a structural damage grows. In the following we scrutinize this very idealized view. It is assumed that a damage is initiated and starts to grow at the manufacturing defect after a certain time of operation. This limit is called fatigue life and the according allowable load spectrum is called fatigue strength. However, it can be expected that some complex physical processes lead to this damage growth threshold if manufacturing defects are present. Actually, two reasons can be identified. At first
the defect causes a finite stress concentration and the material reaches its therefore lowered fatigue strength under cyclic loading. If we think of the defect as a small hole in the structure (cf. figure 5) we formally can assign a notch factor to this stress concentration, say e.g. $\alpha = 3$. It is plausible and also indicated by the test results in figures 3 and 4 that the fatigue strength is lower than the initial static strength and that the fatigue strength decreases as the severity of a manufacturing defect increases. Damage initiation occurs if the cumulation of the far-field stress – oscillating with amplitude $\sigma_a$ and concentrated by $\alpha$ – exceeds the endurance fatigue limit $S_e$ of the undamaged (unnotched) material. For constant-amplitude cyclic loading the fatigue strength, i.e. the allowable stress amplitude $S_a$ may show a linear dependency on the number $N$ of cycles in a double-logarithmic diagram, i.e. $S_a = S_e (N/N_e)^{-1/k}$. This so-called line of Wöhler can be typically drawn for metals for high cycle fatigue loading with good accuracy. Also some composite materials allow this simplification by accepting a higher variance from this line [5].

If the so introduced damage is a simple crack or a delamination the second physical reason which finally causes the damage to grow is a stress intensity at the tip of this damage. Damage grow occurs if the range $\Delta K$ of the oscillating stress intensity factor is larger than a threshold value $\Delta K_{th}$, i.e. larger than this endurance limit for crack grow. According to simple linear fracture mechanics the range of the stress intensity factor at the crack tip is formally $\Delta K = \Delta \sigma Y(a) \sqrt{\pi a}$ where $a$ is the length of the crack and $Y(a)$ is a function defined by the crack geometry and the location of the crack. When exceeding the threshold value $\Delta K_{th}$ the damage will grow following some constitutive relation. This finally yields curves as sketched in the lower diagrams of figures 1 and 2. Paris’ simple law $da/dN = C(\Delta K)^m$ may be applied for cracks in metals but is certainly insufficient for progressive damage of composite materials. The damage mechanisms in composites are typically much more complex than a simple crack or a delamination; particularly when manufacturing defects are present. For example, progressive damage can be initiated and advanced by microscopic inter-fiber matrix cracking. The crucial point now is that the parameters of both theories, initial damage and initiation of damage growth are determined by different test setups and test specimens. For fatigue strength tests small coupons are used. For damage growth tests simple structures are used which are sufficiently large to observe stable damage propagation. However, to draw finally curves as in the lower diagrams of figures 1 and 2 the theories of damage initiation and of the following progressive growth of the damaged area shall match consistently.

For example, consider an oscillating stress concentration with constant amplitude $\alpha \sigma_a$ at the manufacturing defect. The fatigue strength $S_a = \alpha \sigma_a$ of the material is reached after $N$ cycles and a significant macroscopic, i.e. measurable or even visible crack is introduced. Let $a_0$ be the length of this initial crack which now causes a stress intensity. The far-field stress level to consider for the crack tip is the stress influenced, i.e. concentrated by the defect. The determining stress range for crack grow is thus $\Delta \sigma = 2\alpha \sigma_a$ near the defect. For an initial crack length $a_0$ (and therefore a crack tip distance) which is much larger than the size of the defect the stress range reduces to $\Delta \sigma = 2\sigma_a$. A following growth requires then $\Delta K = 2\sigma_a Y(a_0) \sqrt{\pi a_0} > \Delta K_{th}$. Since $S_a > S_e$ the endurance limits for both damage growth reasons, initial stress concentration and following stress intensity, should therefore be – at least – related by

$$\Delta K = 2 \frac{S_e}{\alpha} Y(a_0) \sqrt{\pi a_0} \approx \Delta K_{th} \quad (1)$$

For metals this condition is typically quite well fulfilled with reasonable values $a_0$ determining the transition between crack initiation and crack growth. For example, consider the aluminum alloy 2024-T3 which has the material limits $S_e = 104 \text{ N/mm}^2$ and $\Delta K_{th} = 87 \text{ N/mm}^{3/2}$ for cyclic tension-tension loading $R = 0$ [6]. Assuming the geometrical values $\alpha = 3$ and $Y(a_0) = 1$ relation (1) yields a transition crack length of at least $a_0 = 0.5 \text{ mm}$. For composite materials much more constitutive parameters are involved which will certainly complicate an according
Figure 3. Stiffness degradation and residual strength of specimens with a defect (out-of-plane undulation). The stiffness degradation is measured continuously during the fatigue strength test whereas markings correspond to the single residual strength measurements.

analysis. However, equations similar to (1) may be derived to check consistency and to match the theories of damage initiation and of the following progressive growth of the damaged area.

Another aspect concerns the residual strength curves, i.e. the development of the static strength after a certain fatigue load spectrum. The upper diagrams in figures 1 and 2 indicate that the initial strength is lower for a more severe manufacturing defect and that the residual strength further decreases as the damage grows. This assumed behavior is based on the experience with metallic materials where the residual strength of a cracked structure is associated with the fracture toughness $K_c$. If the stress intensity factor $K = \sigma Y(a)\sqrt{\pi a}$ at the crack tip is larger than this material parameter, $K > K_c$, unstable crack grow sets in. Since the stress intensity factor $K$ increases as the damage, i.e. the crack length $a$ increases, the residual strength, i.e. the allowable stress level $\sigma$ to reach structural failure decreases. Although this conclusion sounds plausible it is particularly for composite materials not necessarily true.

Figure 3 presents test results obtained with specimens having an artificially introduced defect. The test specimen is a standard coupon with $2\text{ mm} \times 25\text{ mm}$ cross-section and with six uni-directional layers, i.e. all fibers are pointing in so-called $0^\circ$ loading direction. Between the outer layers deliberately introduced resin deposits force an out-of-plane undulation of the fibers. Figure 3 shows the degrading stiffness of the material during a cyclic fatigue loading (in the current case a tension-compression loading $R = -1$). As the number $N$ of cycles increases the curve passes three regions which is typical for this kind of material (cf. also figure 4). At first the curve shows a strong stiffness decrease, then a linear decrease (here on a linear scale and not on logarithmic one), and finally again a strong decrease towards total failure of the specimen. The constant load amplitude applied in this test is the fatigue strength for the gained number of cycles until total failure. In figure 3 this value is plotted in relation to the initial strength under static loading.

Figure 3 shows also a few residual strength measurements. It shall be noted that drawing a residual strength curve is a laborious procedure. After a certain number of fatigue load cycles the fatigue test is stopped and a static strength test follows. Whereas the whole stiffness degradation curve is already shown by one specimen, each measurement point along the residual strength curve needs one specimen to be spent. However, the measurements in figure 3 indicate that remarkably the residual strength increases as the number of cycles, i.e. the fatigue loading increases. An explanation for this partly surprising behavior may give the tests presented by [7] which results are summarized in figure 4. Analogously, specimens of $38\text{ mm}$ width but having a hole of $9.5\text{ mm}$ diameter undergo a cyclic fatigue loading with a following residual strength test.
Both, the stiffness degradation curve and the residual strength curve show a similar behavior than in figure 3. The reason is found out by X-ray radiography in [7]. The stress concentration at the hole increasingly deteriorate the material around the hole as the fatigue loading continues (cf. figure 5). This massively damaged area acts like a bigger hole which in turn yields a lower stress concentration during the following residual strength test. Similarly the fatigue loading at the defect depicted in figure 3 may cause a local deterioration of the material at points of stress concentration which further results in a relief of this highly stressed regions in the following residual strength test.

The results presented in the preceding paragraph reveal a diametrical different strength behavior of metals and fiber-reinforced composites under cyclic and static loading. On the one hand, as depicted in figure 5, ductile metals react on high static loading with yielding at points of stress concentration. The cross-section does not fail until all the material yields. Typically, fiber-reinforced composites do not show this damage tolerant behavior under single static loading. Particularly in fiber direction they show a nearly linear-elastic behavior until failure. Static loading causes the brittle fibers to fracture at points of stress concentration. The load carrying capacity of the whole cross-section is then suddenly reached. On the other hand, cyclic fatigue loading causes crack initiation in metals. The stress intensity at the crack tip further reduces the residual strength dramatically. Contrarily, the deterioration of composite materials in areas of stress concentration may yield an advantageous relief of the material in a following high static loading. Nevertheless the composite material is damaged after fatigue loading. The nominal increase of the residual strength in figures 3 and 4 indicates rather a certain damage tolerance than showing a potential for technical use, i.e. weight saving. Moreover, for many lightweight applications as e.g. automotive structures, the determining design criteria is the structural stiffness, which definitely decreases as the fatigue loading continues.

4. Conclusions
The brief discussion of the currently applied safety concepts for composite aircraft structures in section 1 concludes that the state-of-the-art safe-life flaw tolerance concept is not weight-optimal. It is suggested to enhance the damage tolerance approach which originally was developed for metallic materials (cf. figure 1). Thereby it is also emphasized that such a modification requires
Figure 5. Notch sensitivity of metals and composites under static and cyclic loading.

definitely the consideration of manufacturing defects, which are in many cases the origin of subsequently growing damages. Section 2 presents how this modification can be introduced in principal (cf. figure 2) and how design guidelines with such an enhancement could work.

However, the presented damage tolerance diagrams show a very idealized view on the effects of manufacturing defects and growing damages. Apart from the difficulty to identify, respectively define damage initiation the discussions in section 3 reveal that the static strength and residual strength behavior of metals and fiber-reinforced composites is diametrical different (cf. figure 5). In fact, the residual strength of composite materials may increase after a certain cyclic fatigue loading (cf. figures 3 and 4). These results show that residual strength measurements need a careful interpretation, first when drawing conclusions regarding the implications of growing damages caused by manufacturing defects and second when drawing damage tolerance diagrams to develop monitoring strategies.

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