

Aspects of Damage Tolerance and Fatigue of CFRP Structural Components

Uli Burger

Technische Hochschule Ingolstadt

Ludovic Rochat

Institut für Technik und Design GmbH

ABSTRACT

Lightweight structures are one key issue for all future mobility concepts. Carbon fibre reinforced plastics (CFRP) play an important role in these disciplines due to their outstanding mechanical performance regarding to their weight. Therefore, CFRP structures have been widely used since decades in aerospace industry resulting in improvements in payload, fuel consumption and range. The Airbus A350, Boeing B787 in civil airplane industry as well as military products like the NH90 transport helicopter are examples of this development towards "all composite"-aircrafts.

A main difference of CFRP-structures towards metallic ones is the behaviour regarding damage tolerance and fatigue. For helicopter composite structures this issue is newly defined in §573 of the relevant certification specifications (CS and FAR). This paper summarizes the necessary efforts and possible methods to show compliance for this specific topic in the aerospace industry to design robust and lightweight CFRP structural components.

Methods to predict accurately damage propagation in composites via increasingly powerful numerical tools are presently widely investigated. Numerical derivation or at least relevant approximation of design allowables of laminates made of any sequence of laminae would be a great achievement making doubtlessly the overall design process cheaper and shorter. In this paper, a new methodology is proposed to simulate progressive damage occurring after low velocity impact (LVI) and to assess the residual strength of pre-damaged plates submitted to compressive loading (Compression After Impact). These numerical analyses are carried out with the FE commercial code Abaqus/Explicit. The relevance of the FE results is assessed through correlation with experiments.

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INTRODUCTION

Over the last decades, composite materials have increasingly been used in the aerospace industry: the high specific strength and stiffness, the resistance to corrosion, reduction of number of parts, crashworthiness, fatigue resistance and tailorable properties make polymeric composites very attractive (1).

The Windecker Eagle made of GFRP was the first all-composite aircraft to comply with the FAA regulations and to be certified in the US in 1969. Since then and with the introduction of advanced composites in the 1980s such as the CFRP, these materials are no more only used for secondary loading structures such as the rudder, spoilers, airbrakes, elevators and flaps of the A320. Applications nowadays include the wing box and fuselage of the new generation of long-range transport aircraft including the B787 and A350 whose percentage of their structural weights attributed to composites are around 50%.

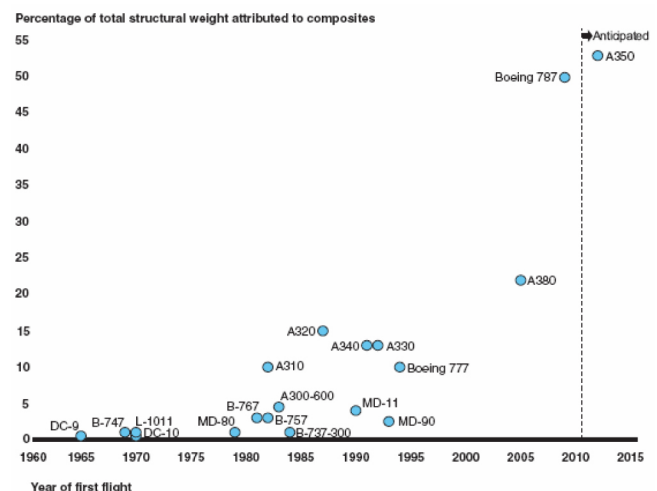


Figure 1. Proportion and evolution of composites in commercial airplanes (2)

REGULATIONS IN THE AEROSPACE INDUSTRY

The regulations CS for the EU and FAR for the US provided respectively by the airworthiness authorities EASA and FAA, usually harmonized, and regularly updated and refined. For an aircraft to be certified in the relevant countries, its design has to show compliance with these regulations. The four documents CS(FAR)23-25-27-29 deal with regulations for respectively small aeroplanes, large aeroplanes, small rotorcraft and large rotorcraft.

Definitions

The following definitions, generally common to all the CS and FAR documents, are given below to clarify the airworthiness regulations in terms of fatigue evaluation discussed in the next paragraph (3, 4, 5):

- **Damage tolerance:** The attribute of the structure that permits it to retain its required residual strength for a period of use after the structure has sustained a given level of fatigue, corrosion, or accidental or discrete source damage.
- **Fail-safe:** The capability of structure remaining after a partial failure to withstand design limit loads without catastrophic failure within an inspection period.
- **Safe-life:** The capability of as-manufactured structure as shown by tests, or analysis based on tests, not to initiate fatigue cracks during the service life of the rotorcraft or before an established replacement time.
- **Fatigue safe-life:** Structure must be shown to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks.
- **Design limit load:** The maximum loads to be expected in service.
- **Ultimate load:** limit load multiplied by prescribed factors of safety.
- **Residual strength:** The strength retained for some period of unrepaired use after a failure or partial failure due to fatigue or accidental or discrete source of damage.
- **Principal structural element (PSE):** A structural element that contributes significantly to the carrying of flight or ground loads and whose failure (such as fatigue cracking) can lead to catastrophic failure.
- **Catastrophic failure:** Any structural failure, which results in death, severe injury, or loss of the aircraft.
- **Accidental damage:** Discrete damage that may occur in service use or in manufacturing due to impacts or collisions, such as dents, scratches, gouges, abrasions, disbonds, splintering and delaminations.

Principal structural elements (PSE) include all structural elements susceptible to fatigue cracking which can lead to catastrophic failure such as:

- Aeroplanes: wind and empennage (control surfaces, spars, skin-stringer combination, primary fittings and spliced), fuselage (circumferential frames, door frames, window frames, pressure bulkhead), landing gear and engine mounts

- Rotorcraft: rotor blades including the attachment fittings, rotors head (hub, dampers, hinges), rotor supporting surface, landing gear, fuselage and auxiliary lifting surfaces

Damage Tolerance and Fatigue Evaluation

Damage tolerance and fatigue evaluation of composite structures are addressed in §573(a) for CS(FAR)-23, in §573 for CS(FAR)-27 and 29 and in §571 for CS(FAR)-25.

The regulations are accompanied by Acceptable Means of Compliance (AMC for CS) and Advisory Circulars (AC for FAR). These documents provide example of acceptable means of showing compliance. Even if they are not mandatory, the guidance reflect the present good design practices and are generally followed by the aerospace manufacturers in order to facilitate the certification. The means of showing compliance AC No 20-107B and AMC 20-29 deal specifically with composite aircraft structure (6).

The evaluation of the composites structure must show that no catastrophic failure will occur during the operational life of the aircraft and has to deal with the static and repeated loads, adverse environmental effects, manufacturing defects and accidental damage. The so-called “damage tolerance fail-safe” and “fatigue safe-life” evaluations (defined above) are the two possible design approaches. The latter is considered only if the former is “impractical within the limits of geometry, inspectability, and good design practise” (7). The damage tolerance evaluation should include the PSE.

The damage tolerance evaluation procedure is given below:

- Identification of the parts being evaluated
- Determination of the critical load cases expected in service including the fatigue (repeated) load spectrum that contribute to damage growth
- Damage threat assessment: determination of the types of damage that might occur during manufacturing, maintenance or operation. Depending on the damage severity and considering the tools available for inspection
- Determination of the residual strength of the structure: one should demonstrate that the residual strength of the structure will be above the strength required to withstand the design loads. The sensitivity of the structure to damage growth has to be controlled (crack stoppers and multiple load paths) to ensure adequate residual strength. It has to be ensured that the residual strength doesn't remain during an excessive period of time below the strength required to retain ultimate load. (see Figure 2)
- Replacement times and inspection: frequency, extent and methods defined the maintenance plan whose goal is to restore ultimate load capability of the structure. The inspection interval depends on the damage detectability threshold, depending itself on the inspection methods used. Inspection intervals should be set between the time the damage is initially detectable and the time the damage severity reaches the limit corresponding to critical residual strength capability. (see Figure 3)

- Effect of damage on the stiffness and dynamic effects should be considered since strength is not always the driving criterion to size structures such as the wings (stiffness-based criterion).

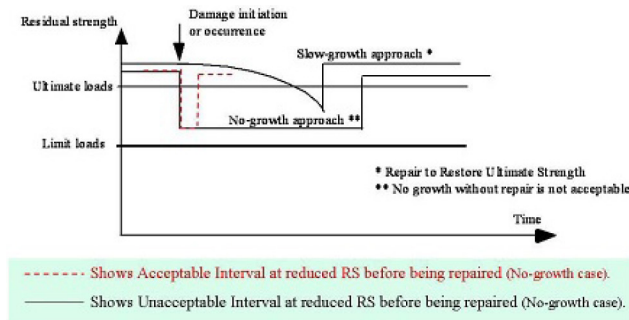


Figure 2. Schematic diagram of residual strength accounting for damage occurrence and repair (6)

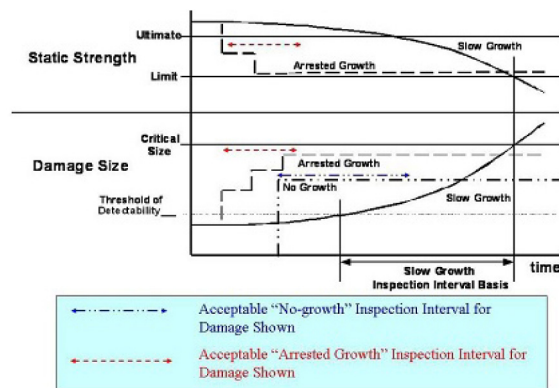


Figure 3. Residual strength and damage size relation, acceptable inspection intervals (6)

If the damage tolerance fail-safe evaluation is impractical then a fatigue safe-life evaluation is then performed. Fatigue substantiation should account for the effects of the environment and for the flaws and accidental impacts that might occur during manufacture, maintenance and operation.

GENERAL APPROACH

Damage Tolerance and Fatigue for CFRP vs. Metals

The procedure presented above in terms of damage tolerance and fatigue evaluation is similar for metallic and CFRP structures (critical loading, threat assessment, determination of residual strength and inspection programme). The difference remains in the way the procedure is implemented since the impact responses and fatigue characteristics (damage initiation/evolution) have nothing in common: whereas their assessment for metallic parts is rather straightforward and relies on empirical equations from tests and experience, no database is available for composites due to the variety and complexity of their failure modes (see Table 1).

Table 1. Metal fatigue compared with composite fatigue (8)

	Metal	Composite (CFRP)
Crack initiation	Stress concentration, voids	Stress concentration, voids, micro-cracks, fiber debonding, fiber discontinuities, misalignment
Crack propagation	Single crack growing	Propagation of multicracks through matrix and fibre/matrix interface
Final failure	Clean fracture surface	Combination of matrix cracks, debonding, delamination (sublaminar buckling) and fiber breakage

Moreover, CFRP structures are very sensitive to out-of-plane loads. Low velocity impacts (such as dropped tools) are of great concerns since they are likely to be undetected (barely visible impact causing internal damage such as delamination) while decreasing significantly the load-carrying capacity of the structure (9, 10, 11).

Threat Assessment

Starting point for the damage tolerance methodology must be a proper assessment of realistic impact energy levels. A part-by-part analysis is recommended as threats may easily differ regarding to the design properties, location and functions of the PSE. Data may be derived out of in-house experience, customer support data or from literature. Regarding H/C-structures (sandwich), an overall assessment is given in (12) and shown in Figure 4.

In this diagram different identified impact threats are given with their corresponding energy level and their probability. For instance, 99% of the terrain object impacts occurred at max. 50 Joules. This has then to be matched with the single PSE whether it is feasible or not. Deeper insight regarding single models or components are derived by in-house-investigation and customer support data.

Detectability Thresholds

As stated before damage detection for composite structure points out to be a real challenge because of the possibility of large invisible damage inside the structure which cannot be seen from outside. For practical reasons only means of visible inspection should be considered for defining the detectability of damages. Different methods and definitions are given in (13). A possible mean for defining detectability of damage is the dent depth after an impact event. An investigation by Airbus shows that dent depths of 0.3mm and higher are detected by 100% (Figure 5) and can serve as a first value for detectability of damage. The investigation was carried out with blue collar workers and by so called “detailed visual inspection”. This means close proximity to the structure (max. arm length), possible cleaning of surface, sufficient and if needed additional light and simple additional means like magnifying lenses.

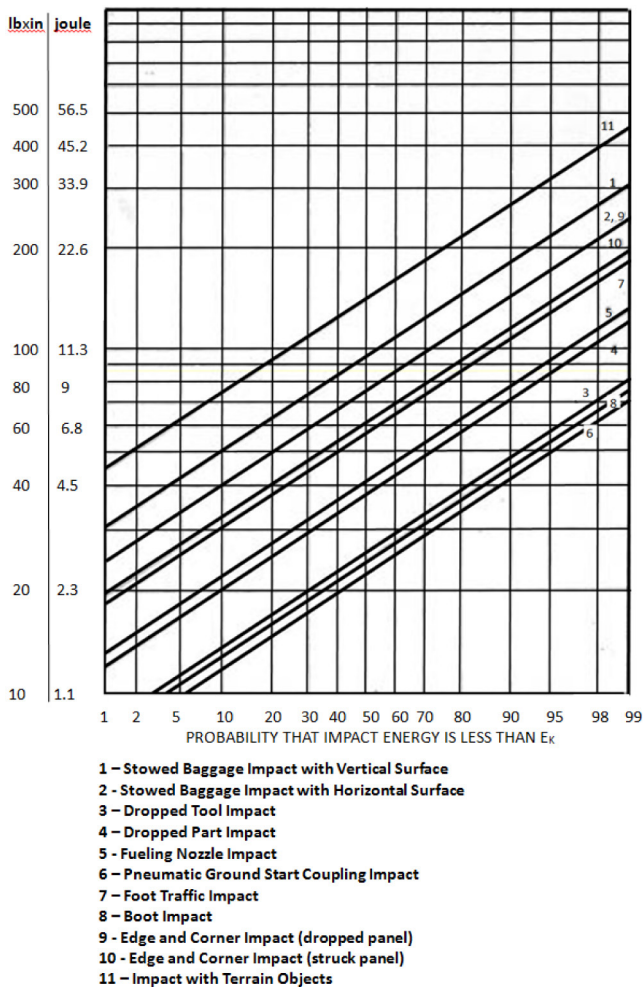


Figure 4. Possible impact energy level for airframe structure (12)

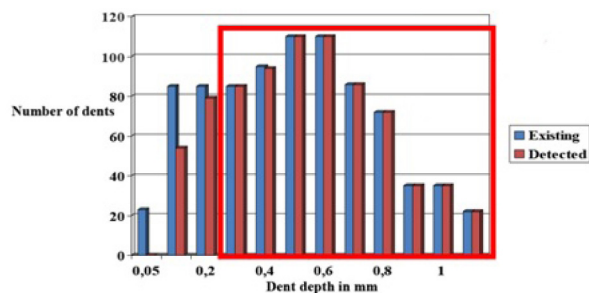


Figure 5. Dent depth detectability by detailed visual inspection (15)

This threshold is known as barely visible impact damage (BVID). This value is also given in (20) where testing procedure for composite coupons is given. The influence of boundary conditions such as time, loading and environmental effects has been studied by another investigation. The results are shown in Figure 6.

From this figure, it can be clearly seen the significant effect by hot/wet ageing to the evolution of the dent depth. Hot/wet ageing is used as a laboratory artificial means to simulate effects of humidity and temperature during life time for composite parts. In general the coupons are stored in a climatic chamber for 1000 - 1500h at 70°C and 85%r.H. until saturation. This effect is known as relaxation meaning that the impact dent depth will decrease if not detected

directly after the impact event. This has therefore also to be considered when defining the detectability threshold. Common values can be found in (13) and a dent depth of 1mm commonly used as threshold for detectability of impact damage.

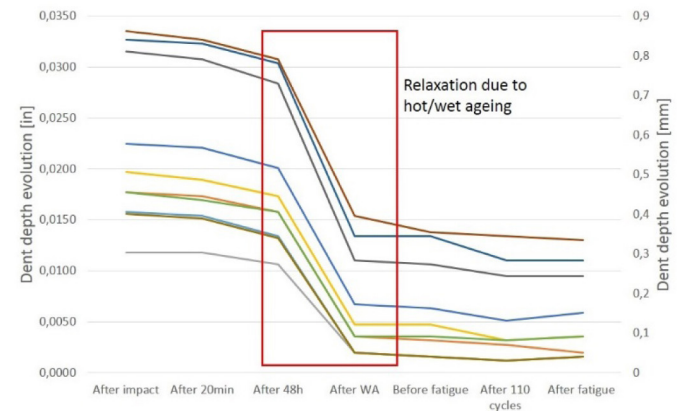


Figure 6. Relaxation effects on dent depth (15)

Impact dent depths which can be found by inspection are considered as visible impact damage. Upper bound before being considered as obvious damage is known as clearly visible impact damage (CVID). Surface damage like fibre breakage are immediately considered as obvious damage regardless of the dent depth and require more detailed inspection and repair.

The corresponding energy level necessary to obtain the dent depth is strongly dependent to the layup and material used and must therefore be defined individually for every PSE.

Zoning Diagram

Putting together the information of threat assessment and detectability of damage leads to a zoning diagram (13) in general which can then be applied to every PSE individually.

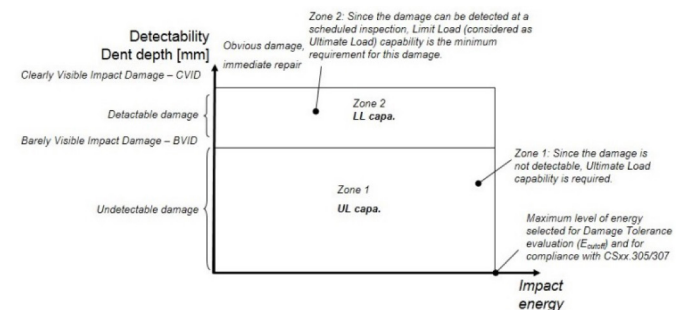


Figure 7. General zoning diagram for PSE accord. to (13)

Damage caused by possible threats with a dent depth lower than the BVID threshold is considered as undetectable. Therefore ultimate load capability is necessary together with a no-growth of damage during the whole life-time of the structure. This zone is called Zone 1. The region of damages with dent depths between BVID- and CVID-level is called Zone 2 and sets to be the damage tolerant zone. Within this zone the structure must have limit load capability and no-growth of damage during one inspection interval is mandatory. During inspection damage will be found and ultimate load capability