ABSTRACT
The extend of impact damage in sandwich structures depends on the core material and the stacking sequence of the sandwich skin laminate, the size, mass and velocity of the impactor and on the ability of the component to absorb the shock at the impact point. Because of the complex interaction between these parameters the forecast of the damage and the progress under Tension-Tension (T-T), Tension-Compression (T-C) and Compression-Compression (C-C) fatigue loading is difficult to conduct. Impact damage is most critical, when the skin remains intact. Except of a small dent or blister in the skin surface the impacted zone is often barely visible. Nevertheless, the damage may grow under fatigue loading to a critical size, where the component is endangered. In sandwich structures with foam core a delamination will be detected most likely around the impacted zone between skin and core. The damage progress is triggered by the local buckling of the delaminated skin layer. In structures with Honeycomb core delaminations are hardly detected after impact (see Figure 1). The core is crumpled in the vicinity of the impacted zone and the elastic support of the skin layers is reduced. Under compressive loading the core shrinks in thickness direction and the skin layer may buckle in core direction.

INTRODUCTION
The impact damage can be analyzed by 3D-elements, often combined with extended plate elements for the skin layers. Due to the large deformations the postbuckling behavior of the growing damaged zone must be considered. This kind of analysis is quite expensive and will hardly be applied to actual damage configurations. In order to overcome these disadvantages the Analysis Tool

COmposite Damage Tolerance Analysis Code (CODAC) as a Windows and NT compatible computer program was developed. The model is complex enough to cover the essential geometrical and damage configurations and it is numerically inexpensive enough to perform trend analyses of the damage growth in reasonable time. The analysis tool contains free parameters in order to achieve conservative results. With CODAC, an impact damage can be forecasted and/or a detected impact damage can be analyzed in a sandwich plate. Also trends for the damage growth can be evaluated, which allows a first estimation of the damage tolerance behavior of the structure. Additionally it can be used to establish guide lines for the design.

As can be drawn from experimental results in the open literature, high stress concentrations appear at damaged zones in structural components which lead to additional damages combined with a damage growth and ultimately to a failure of the component. The so long accomplished researches however show, that fiber-reinforced plastics (FRP) are able to reduce (disintegrate) stress concentrations at notches or damages (such as impact damage) by stress rearrangements (“Notch Root Blunting Effect”). In different researches it was found that the life characteristics (S/N curves) of undamaged and damaged structures are narrowing each other with increasing numbers of load cycles and are intersecting in the range of N = 10⁶ to 10⁷ load cycles (LC). This leads to the fact that damaged structural components have the same durability as undamaged components at relative very low load levels. These results were mostly stated in relevant investigations with solid laminates manufactured from Prepregs. Only rare experiences are available at this time for structural components out of fabrics and especially out of sandwiches. Therefore investigations were carried out with numerous sandwich samples the skin of which was build up with unidirectional CFRP-Prepregs as well as CFRP- and GFRP-fabrics with different fiber orientations and stacking numbers.
The core itself consisted of Nomex-Honeycomb with different thickness and weight per volume.

In the test program undamaged test pieces as well as tests samples after impact were investigated under quasi-static as well as fatigue loading. The impacts were generated by means of an improved computerized impact testing machine (different values of energy and measurements of time depending load and depth of penetration). The quasi-static tests for the determination of characteristic materials data of stiffness and strength for the different test-configurations were executed with pure material test samples and sandwich specimens under tension and compression loading. The relevant fatigue tests comprised alternating loads in the TC-load regime with R = -1 in two different test modes:

- Fatigue tests in one load stage for every individual test sample cycled at one load level up to ultimate failure or fracture;
- multistage fatigue tests for every individual test sample loaded at different load levels in a block diagram.

The results of both the test procedures were compared via statistical methods and models (such as Miner Rule). During the tests the load and the global distortion - and by this the stiffness change - was measured continuously. In addition an optical microscope was used to detect and measure cracks and delaminations at the surface. For the judgement upon type and extent of impact damages and for the characterization of the damage propagation during the fatigue loading some of the specimens were recorded by X-ray and/or ultrasonic C-scans.

**ANALYSIS TOOL CODAC**

**Analytical methodology**

Figure 2

Figure 3

Figure 4

**Numerical results**

Figure 5

Figure 6

**Analytical/experimental correlation**

Figure 9

**SANDWICH STRUCTURAL ELEMENT**

**Composite sandwich**

Figure 10

**Impact behavior**

Figure 11

**Damage detection and assessment**

Figure 12

Figure 13

Figure 14

Figure 15

**RESIDUAL STRENGTH**

**Static loading**

Figure 16

Figure 17

Figure 18

Figure 19

**Fatigue loading**

Figure 20

Figure 21

Figure 22

**Damage detection and assessment**

Figure 23
CONCLUSION / OUTLOOK
REFERENCES


Figure 1 Deformation of Skin and Honeycomb Core of a Sandwich Element

Calculation of damages

- Subdividing of elements in „Units“
- Calculation of stresses for each Unit across laminate thickness
- Application of the damage criteria for the evaluation of:
  - Fiber breakage
  - Matrix cracking
  - Delaminations

Figure 2 Analytical Methodology

Figure 3 Buckling analysis with CODAC *

* COnposite Damage tolerance Analysis Code
Enhancements of CODAC include:

- Extension of CODAC for application to stringer-stiffened structures
- Enhanced method for assessment of the complete 3D stress tensor for the 2D FE Method
- Impact locations from mid-bay impact to impact in the area of the stringer-foot
- Enhancement of the buckling analysis to account for quasi-static delamination growth
- Implementation of various damage criteria for fibre breakage, matrix cracking and delamination (Hashin, Puck, Choi/Chang, etc.)

Figure 5 Composite structural element (wing) used as a first benchmark

Figure 6 Numerical results with CODAC for damages in skin laminates

Figure 7 Transient analysis with CODAC in comparison with experiments

Figure 8 Numerical results with CODAC

stringer stiffened CFRP panels, impact in the mid-bay
Figure 9 Analytical / test correlation
stringer stiffened CFRP panel impact in the mid-bay

width = 100 mm
160 mm

Figure 12 Damage detection in sandwich elements
skin delaminations after 10 Joule impact

Impact 5 Joule 10 Joule 15 Joule

Figure 13 Damage detection in sandwich elements
global damage in 160 mm wide samples

Impact 5 Joule 10 Joule 15 Joule

Figure 14 Damage assessment for analysis tool
global damage in 160 mm wide samples

Figure 11 US-Inspection of a Sandwich with
4 (top) and 18 (bottom) Joule Impact

C-Scans of
B-Scans through
the backwall echo of whole thickness

Width 160 mm 100 mm

Figure 15 Detailed damage assessment for
CODAC skin damages after 5 Joule impact
Figure 16 Undamaged reference specimen

Figure 17 Static Compression after impact (CAI) versus Impact energy, 100 mm wide samples

Figure 18 Global damage after 20 Joule impact 160 mm wide sandwich component

Figure 19 Static Compression after impact (CAI) versus Impact energy, 160 mm wide samples

Figure 20 Impacted (18 Joules) Sandwich Specimen under Fatigue Loading (R = -1)

Figure 21 Effect of impact energy on damage size for honeycomb sandwiches

Figure 22 Effect of impact energy on decrease of fatigue strength of Honeycomb sandwiches

Figure 23 Global and detail damage assessment for CODAC 5 Joule 100 mm wide sandwich component