Fatigue in Alu Honeycomb-c

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properties of the honeycomb 'core' of aluminium 'sandwich panels', as

Honeycomb composite lightweight structures made of aluminium or aramid fibres are used in airplanes, railway carriages and automobiles. These structures are subjected to dynamic loading but hardly any fatigue properties of the honeycomb core exist in current literature (A summary of the state of the art: [1]).

The lightweight panels which were investigated are made of a honeycomb core of aluminium, which is connected by an adhesive layer with two outer sheets of aluminium (Figure 1).

During this project, fatigue tests with failures of the core structure were conducted in parallel with Finite Element calculations. An analytical model was created, which explains the experimental results.

Since the behaviour of the panels is orthotropic, the panels react differently depending on the direction of the loading. For this reason, it is necessary to distinguish between the three directions of symmetry, which are called L, W and T direction (Figure 2).

The walls of the honeycomb cells have different wall thicknesses. This is due to the manufacturing process, where the foils are partly glued together. The glued walls with double thickness are called ribbons (Figure 2). The dimensions of the examined panels are shown in Table 1.

Material	Aluminium
Panel dimensions	138mm x 76mm x 10mm
Face sheet thickness	0.6mm
Honeycomb foil thickness	0.08mm
Cell size	6.4mm
Support distance of the 3-point bending test	102mm

Table 1: Material and dimensions of examined Panels

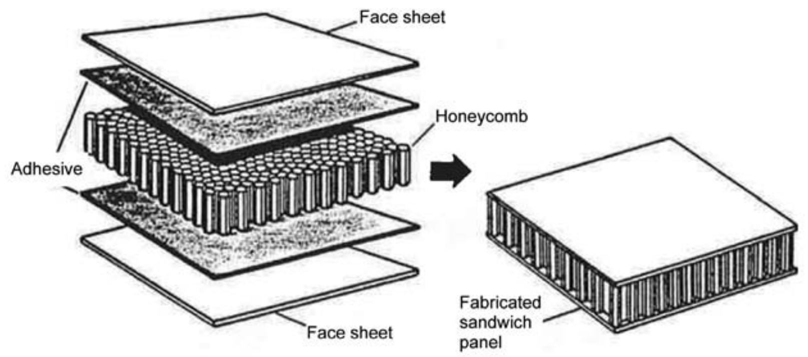

Figure 1: Sandwich structure with honeycomb core [2]

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Failure Modes of Honeycomb core Sandwich Panels

In a 3-point bending test, sandwich structures are mainly subjected to three types of stress:

- Tension / Compression in the cover sheets due to bending
- Shear stress in the core
- Compressive stress in the core in proximity of the load application

Each stress type must be examined in order to figure out which is the critical one.

The bending stress leads to cracks in the face sheets, which was examined in a former project [3].

The core of the sandwich panels usually fails due to shear or compressive stress (Figure 3). The type of stress which prevails, depending of the geometry and the load application, is responsible for the core failure.

The distribution of the stresses in Figure 3 was simulated in ANSYS by moving the load horizontally. The shear stress is maximal somewhere between the two points of the force application. The compression stress in the core has a maximum just below the middle load. Core indentation is occurring, when the compression stress surpasses the buckling strength of the honeycomb core. In this case, the structure fails locally due to buckling of the core (Figure 3).

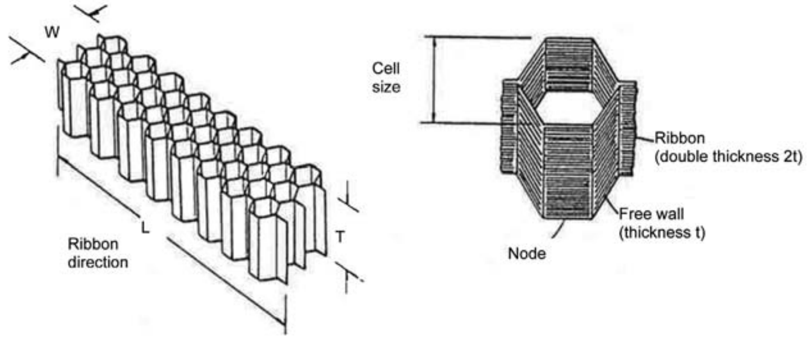

Figure 2: L, W and T directions [2]
(Ribbon has double thickness, due to the manufacturing process)

Materials

The sandwich structure consists of three different materials:

- Glue
- Aluminium alloy AlMg3 H44 (AW 5754) for the face sheets
- Aluminium alloy AlMn1Cu H19 (AW3003) for the honeycomb structure

Test Methodology

Dynamic 3-point bending tests were performed in order to provoke core failure. The test setup is powered by a hydraulic cylinder from Instron Structural Testing Systems (IST). The hydraulic cylinder can be excited displacement or force controlled.

In order to provoke the two failure types of Figure 3, the load was applied in two different ways:

- Steel roll with a small diameter (25mm), which implies a high contact pressure and the component fails by core indentation (Figure 5a)
- Elastomeric roll (Vulkollan 80 Shore A) with a big diameter (76mm), which implies a low

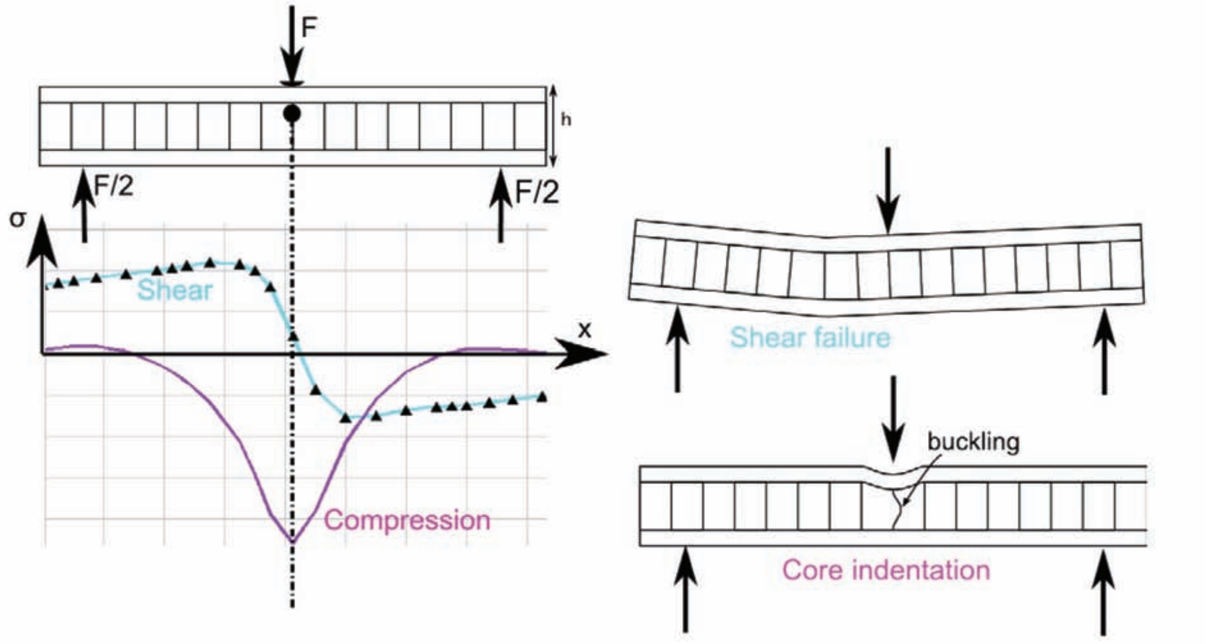

Figure 3: Stress distribution and failure modes of the honeycomb core

contact pressure so that the core fails due to the shear forces (Figure 5b)

Fatigue Test Results

Dynamic tests were carried out to study the fatigue properties of the structure. The samples were loaded in a three-point bending test with a sinusoidal load with constant amplitude at a power ratio of R=10. The excitation was force controlled.

The soft load application (Figure 5b) leads to shear failure in the honeycomb core. Cracks are initiated in the interior of the honeycomb core, which grow predominantly in the diagonal direction of the cells (Figure 6). These cracks are not exactly under the load, but some cells away from it. Here the shear stress is maximal, as shown in Figure 3.

If a hard load application is chosen (Figure 5a), the specimens fail due to the pressure load induced by the load (core indentation). In the damage pattern of Figure 7, it can be seen, that the cracks are exactly under the load application. The W-specimen shows horizontal and diagonal cracks in the cell walls. The L specimen shows only horizontal cracks.

The tests showed that first cracks occurred after less than 10% of the total life period of the specimen. The buckling process creates locally high stresses and cracks, which are not imperatively leading to the total direct failure of the structure.

In Figure 8, the fatigue diagrams of L and W-samples with identical dimensions are shown. In the ordinate of the fatigue diagram the force amplitude is displayed and not the stress amplitude at the location of the crack initiation. These two values are related, but the relationship is not necessarily linear. The number of cycles on the abscissa corresponds to the number of cycles to complete failure of the part and not until the first crack. These boundary conditions imply that the diagrams are not conventional SN-diagrams. The experimental results, however, lie well along a straight line.

The curves of the specimens which fail due to buckling (core indentation), are flat, compared to the shear failure curves. This flat curve is due to the high nonlinear stress increase during buckling.

Simulations

A model of the sandwich structure was created using ANSYS. The structure is modelled with shell281 elements, which have 8 nodes with 6 degrees of freedom each. Shell281 elements are also suitable for large deformations and plastic behaviour. The roll for the load application is modelled with solid95 elements, volume elements with 20 nodes with 3 degrees of freedom each. The contact condition between the roll and the sample is modelled with the elements conta174 and targe170. These elements have 8 nodes and are placed on the surface of the shell elements. Contact occurs when the surface of a conta174 element penetrates one of the targe170 elements.

To make the simulation as realistic as possible, several imperfections are introduced (Figure 9):

- Roll not centred (load inserted on ribbon or next to ribbon) (Δ<1mm)
- Roll rotated around the x-axis, so that the device won't be loaded evenly (α<0.2°)
- Roll rotated around the z-axis (β<0.5°)

	Young's modulus	Tensile yield strength	Tensile ultimate strength	Ultimate strain
AlMg3 H44	69'000 MPa	200 MPa	270 MPa	5%
AlMn1Cu H19	69'000 MPa	190 MPa	265 MPa	2,5%
Glue ST 1035	1'900 MPa		50 MPa	

Table 2: Mechanical properties of the materials used in the Sandwich panels

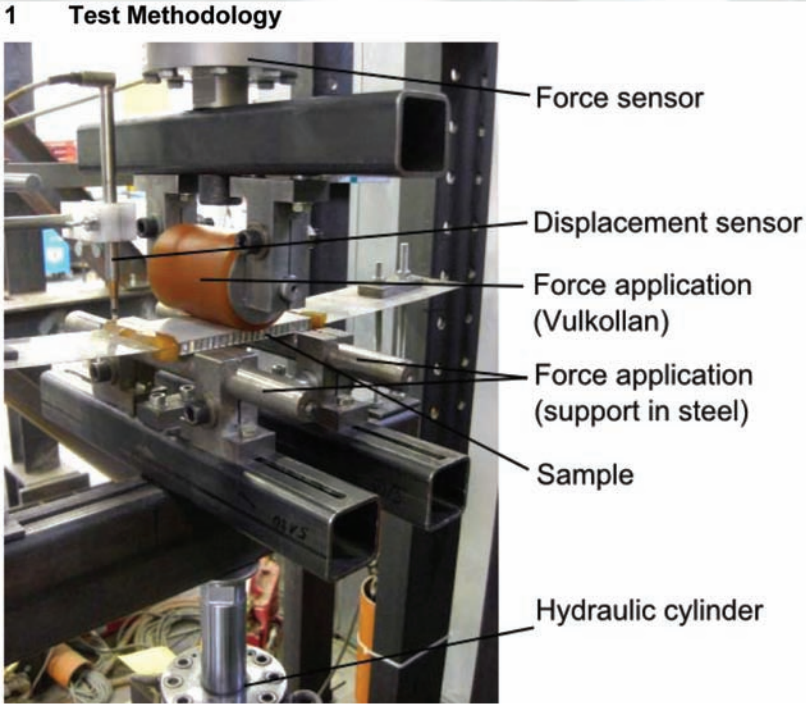

Figure 4: Three-point bending setup used for fatigue testing

- Cells are not regular hexagons (all the coordinates are moved by a small random value) (δ<0.3mm)
- Cells not planar (Small forces (F_i<0.5N) are inserted into the simulation, which dent the walls)

The simulations showed that a rotation of the roll around the x-axis (α) has a big influence. A horizontal displacement of the roll (Δ) can move the force application from a ribbon to a free wall, which also has an influence on the results. All other imperfections are quite insignificant.

The failure of the glue is not the main subject of this article, but it should still be modelled in order to examine the influence of the glue to the buckling load. The adhesive layer covers the honeycomb core and stabilizes it. This overlap is simulated by expanding the shell model of the honeycomb core with two layers of constant thickness, which have the properties of the adhesive (Figure 10). The simulations showed that the influence of the glue to the buckling load is less than 10%.

Core indentation (Buckling of the core)

The experiments have shown that the samples, loaded with the hard roll, failed in the mode of core indentation. Physically, core indentation of honeycomb panels means that the cell walls are buckling (but usually they can still carry loads). The buckling process induces bending stresses in the cell walls, including high tensile stresses. These tensile stresses influence the fatigue behaviour of the core very negatively, so that the crack initiation phase gets much shorter (Figure 8). In most cases however, these local cracks barely influence the strength of the structure.

Some simulations showed however, that it would be too time-consuming to simulate the growth of the cracks (which is very sensitive to imperfections) within this project, in order to see which cracks lead to failure and which cracks not. Therefore, it was assumed that a cyclic buckling of the honeycomb cells is not tolerable if a part is dimensioned against fatigue. In this case, the stresses are distributed more uniformly and the crack growing process is not so important. This assumption does not lead to a big oversizing of the part, because the fatigue curve of the core indentation in Figure 8 is very flat. Therefore, it does not make a big difference if the part is dimensioned for 100,000 cycles or one million cycles (it is assumed, that for 1M million cycles, no buckling is occurring). In the field, core indentation is usually avoided by reinforcing the panel at the position of the load application.

For this reason, honeycomb sandwich structures should be dimensioned so that no buckling occurs, because only in this case can good results be achieved. The buckling load can be calculated by a Finite Element Method in two different ways. First, by a buckling analysis, that calculates the theoretical buckling load for a perfect elastic system (Euler analysis). Alternatively, if nonlinearities have to be considered, the buckling load can be evaluated out of a nonlinear simulation. The contact of the hard load application (Figure 5a) is not very

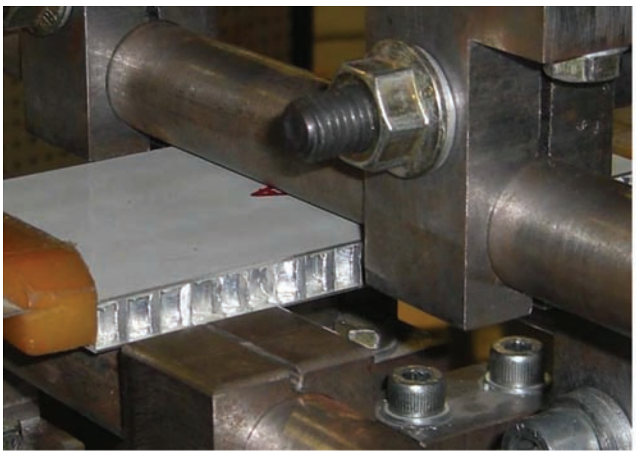

Figure 5a: Hard load application made of steel

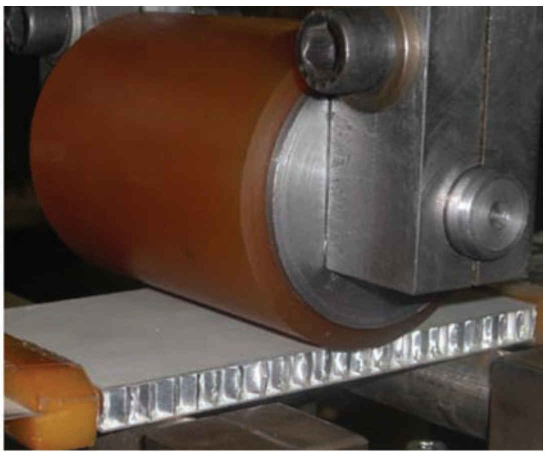

Figure 5b: Soft load application made of Vulkollan

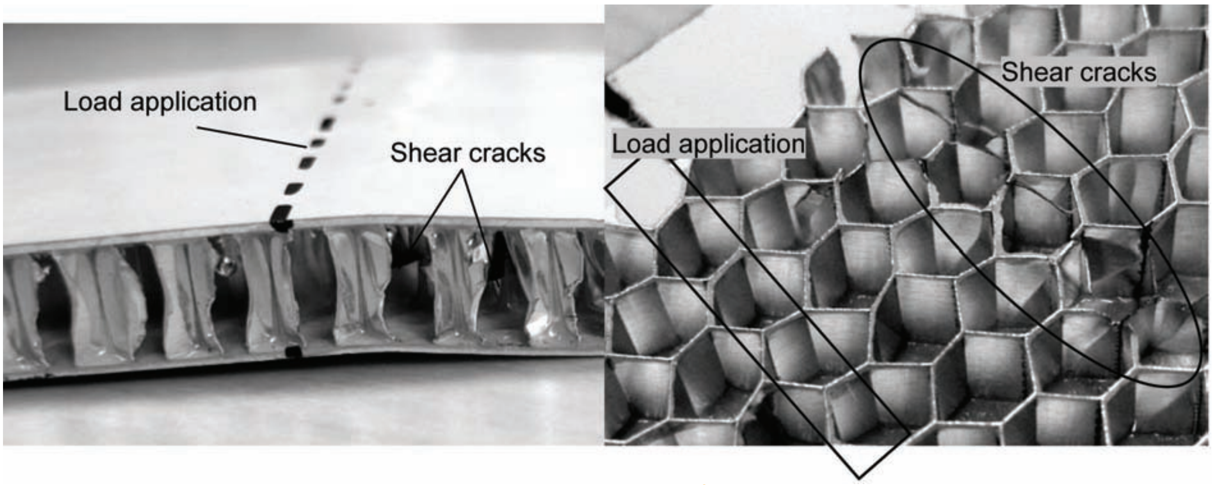

Figure 6: Fatigue Shear failure

load dependant, so that the linear buckling analysis is possible. However, the soft load application (Figure 5b) causes a nonlinear contact condition, so that in this case a nonlinear simulation is necessary.

Shear failure

After proving that no buckling is occurring, a normal static analysis can be accomplished. In this case, the stress state in the core is quite homogeneous and it will be possible to do a fatigue prediction with this analysis. Just under the load application, the compression stress dominates, and next to the load application, the shear stress dominates like shown in Figure 3. When no buckling of the core is occurring, the most damaging stress component in the core is the shear stress. Therefore, the critical location can be determined from a shear stress contour plot. At this location, a fatigue prediction can be accomplished using the FKM-guideline [4].

In a 3-point bending test, away from the load application, the shear stress can be checked analytically:

$$\tau = \frac{Q/n}{t \cdot h}$$

in element coordinates

- τ: shear stress
- Q: shear force
- h: height of specimen
- t: foil thickness of the core
- n: number of cell walls over width

In this formula, it is assumed that the shear stress is distributed uniformly over the honeycomb cells. In the element coordinate system, the angle of the cell walls does not appear in the formula of the shear stress. However, the number of cell walls across the width is important, which implies that the L-samples are much more stable against shear than W-samples (n much bigger for L-samples than for W-samples).

These approximate formulas are just used to understand the influence of the parameters and to check the simulations. In order to have the exact stresses with all local effects, the Finite Element simulations are still needed.

Fatigue analysis of examined specimens

The procedure of the fatigue analysis for the core structure of an aluminium honeycomb sandwich should be as follows:

- Determine the buckling load of the core. Applied load must not exceed this value
- Determine the stresses in a static Finite Element Analysis
- Locate the critical points (e.g. in a contour plot of shear stresses because these stresses are predominating)
- Calculate the lifetime of the honeycomb core, using the FKM-guideline [4]
- Confirm the results when possible by tests

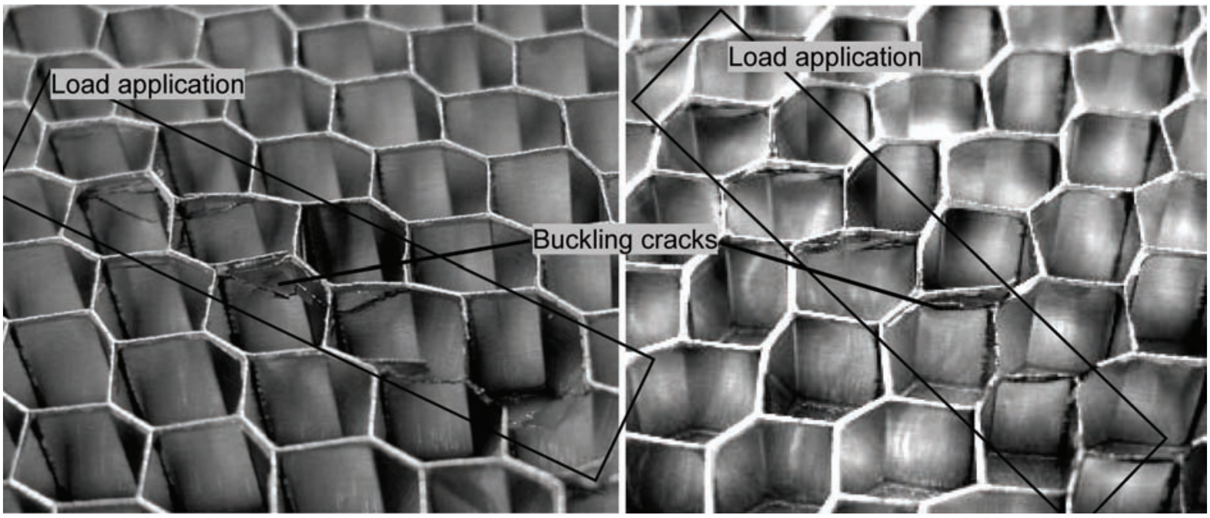

Figure 7: Fatigue buckling failure for W and L specimens

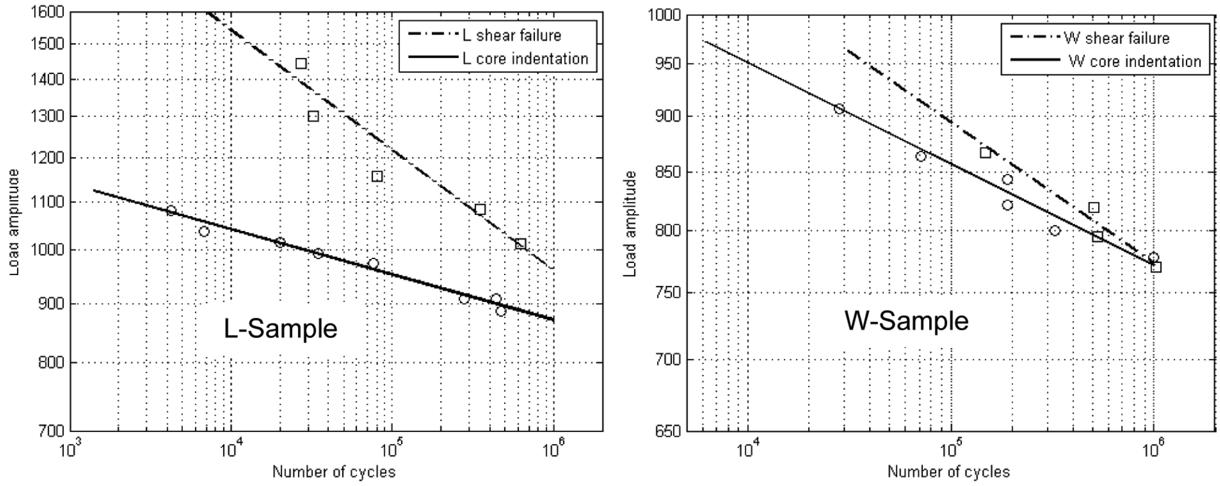

Figure 8: Fatigue strength diagrams for L und W samples

Buckling loads

The buckling loads of different specimens and different load applications are shown in Table 3.

The buckling loads of the soft load application cannot be compared with the test results, because in these cases, the failure mode is not core indentation, and therefore no buckling is occurring. These buckling loads are higher than the failure loads in Figure 8, so the failure is not due to buckling effects, as it is also shown in the experiments.

The buckling load of the hard load application is exactly in the area of the fatigue limit found in the experiments. It was assumed that at the fatigue limit no more buckling is occurring, and so in the experiments the load at the fatigue limit is exactly the buckling load. In these cases, the

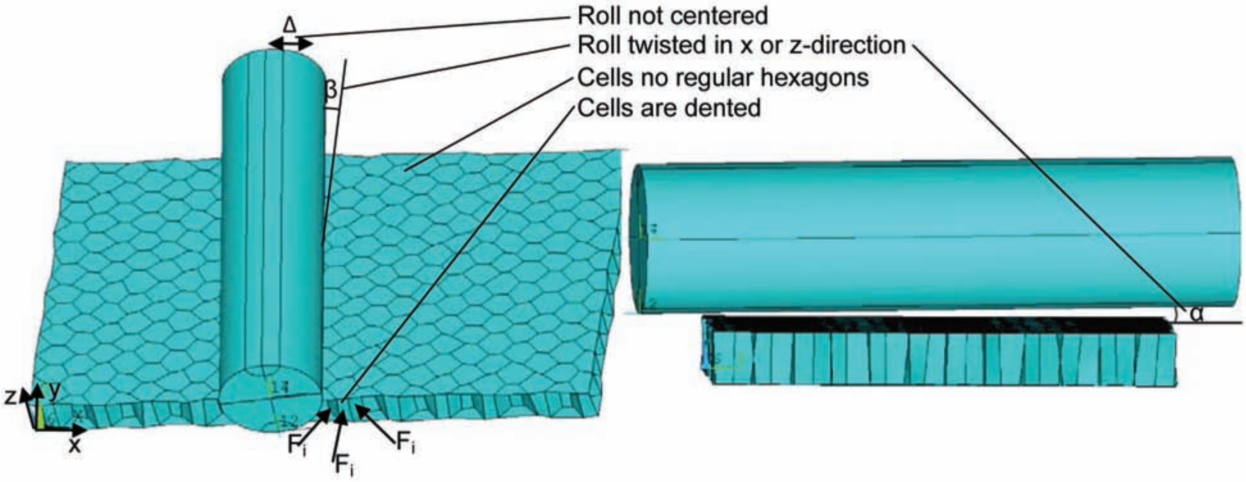

Figure 9: Imperfections included in the simulations (illustrated exaggeratedly)

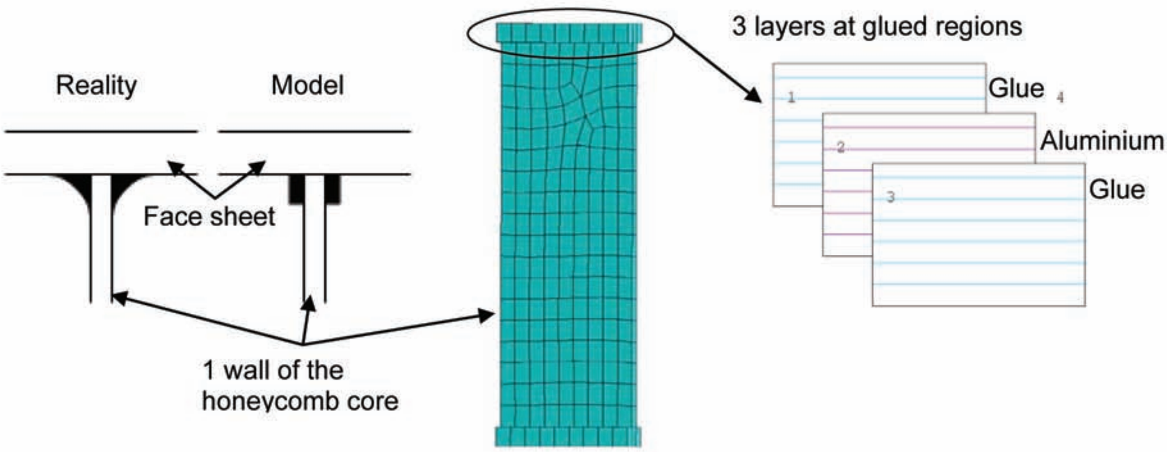

Figure 10: Glue on Honeycomb cells modelled by different layers

endurance limit can be predicted with an accuracy of approximately 10%.

In Table 3, nonlinear analysis means, that the contact surface is changing with load and that the deflections can grow at the buckling load nonlinearly.

Shear failure

When no buckling is occurring, a fatigue analysis is performed using the FKM-guideline [4].

The hard load application leads to core indentation: here, only the soft load application is examined. In Table 4, the results of an L and a W-specimen are compared with the test results.

The lifetime predictions for the two cases examined in Table 4 are conservative. The durability found in the tests was higher than the prediction by a factor of two. This can be considered to be a good prediction [5].

Conclusions

Two different failure modes of the honeycomb core structure were examined: core indentation and shear failure. Core indentation induces buckling of several honeycomb cells. This results in high tensile forces, which will quickly initiate cracks. In practice, components should be designed so that no buckling occurs. The buckling load can be calculated easily with a Finite Element simulation.

The shear failure mode can be analysed by doing a static Finite Element Analysis. Afterwards a lifetime analysis can be done using the FKM-guideline. There were only small differences between the fatigue predictions and the experiments.

The differences between the predicted and the tested lifetimes are only 10% based on stress and only a factor of two in real-life.

Load application	Specimen direction	Simulation method	Buckling load	Test results (fatigue limit)
Hard	L	Nonlinear or buckling analysis	2050N	1933N (equals an ampl. of 870N in Fig. 8)
	W	Nonlinear or buckling analysis	1650N	1711N (equals an ampl. of 770 in Fig. 8)
Soft	L	Nonlinear analysis	2250N	
	W	Nonlinear analysis	1850N	

Table 3: Comparison: buckling load / fatigue limit

Load application	Specimen direction	Load Amplitude (R=0.1)	Simulation method	Predicted life-time	Test results
Soft	L	945N	Nonlinear analysis & FKM	500’000cycles	1’000’000cycles
	W	810N	Nonlinear analysis & FKM	240’000cycles	500’000cycles

Table 4: Life comparison: FKM / experiment

Acknowledgement

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References

[1] Sharma, N.; Gibson, R.F.; Ayorinde, E.O.: "Fatigue of Foam and Honeycomb Core Composite Sandwich Structures: A Tutorial", Journal of Sandwich Structures and Materials 2006 8: pp 263-319

[2] Blitzer, T.: "Honeycomb Technology, Materials, design, manufacturing, applications and testing", first edition, Chapman & Hall, 1997

[3] Bauer, J.: "Ermittlung von Schwingfestigkeitseigenschaften für Leichtbaupaneele mit Wabenstruktur", University of Luxembourg, Faculty of Science, Technology and Communication, PhD-FSTC-5-2008, 2008

[4] Hänel, B.; Haibach, E.; Seeger, T.: "Rechnerischer Festigkeitsnachweis für Maschinenbauteile aus Stahl, Eisenguss- und Aluminiumwerkstoffen – FKM-Richtlinie", 5th edition, VDMA Verlag GmbH, 2003

[5] Schijve, J.: "Fatigue of Structures and Materials", first edition, Kluver Academic Publishers, 2001

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