FATIGUE OF SANDWICH BEAMS UNDER LOCALISED LOADS

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1 Introduction

Sandwich structures offer significant weight savings in many structural applications due to their high stiffness and bending strength to weight ratios. However, one Achilles heal of sandwich structures is their poor capability to carry localized loads.

2 Background

In this paper we investigate the fatigue behavior of sandwich beams subjected to localised loads. Under a localized load, a sandwich structure will deform through bending of the face sheet, which is resting on an elastic/plastic support, the core. At sufficiently high loads, the core will crush (deform plastically). One important basis for the hypothesis of this work is that foams crush in a progressive manner. In a simple compression test, the stress-strain curve has three distinct regimes, as illustrated in Fig.1.

In a compression test of foam core block, up to a certain strain (ε_e) the deformation is linear elastic, regime 1. The limit for linear elastic strains is usually in the order of 2-3%. Under continuing deformation, the core then crushes at almost constant stress, the plateau stress (σ_p), regime 2. At very high strains, usually around 50-75%, the crushed core cells start to come in contact and are being compacted, regime 3. At this strain level, denoted the densification strain ε_d, the modulus increase rapidly.

In a quasi-static indentation test a similar pattern is noticed, but the progression is not as homogeneous as in a simple compression test. The compressive stresses are highest under the point load and at some load the core will start to crush. The load level depends on the yield strength of the core, the bending stiffness of the face sheet and the shape of the indentor. In some sense one now have a compressive test on a cellular scale. As one layer of cells start to crush, they will continue to crush until the strain reaches the densification strain, then the next adjacent layer will do the same. This resembles the compression test depicted in Fig.1, although with a distinctly different shape. There will thus be two distinct strain levels present; either the core is fully crushed with a strain in the order of 50% or so, and in the core which is not crushed, the strain is below the yield point. The second important aspect of this is that the zone of crushed core will grow in a self-similar way. The stress along the crushed/non-crushed core interface must be constant and at, or just below, the plateau stress.

The second important issue is that since the stress along the crushed/non-crushed core interface is constant, it means that increasing load leads to a larger crushed core zone, or rather, and increasing length of the interface, as schematically illustrated in Fig.2. A model for quasi-static indentation response for this problem was developed in [1].

3 Aims and scope

The scope of this investigation is to study the same problem but for fatigue loading. In [2] it was shown that foam cores crush in a similar manner under compressive fatigue loads. However, the difference being that layers of cells crush at lower loads but it requires a certain amount of load cycles before the layer crushes. The hypothesis is this; if one applies a localised load as shown in Fig.2 which is of such magnitude that is does not crush any core, all strains in the system are elastic and no damage will occur. However, if the same load is applied several times, it may lead to permanent damage in terms of a crushed core zone after a certain number of load applications (load cycles). The damage will consist of one or a few layers of crushed cells in a geometry resembling that in Fig.2. Since the crushed core zone will attain a certain size and the interface will have a certain length, the stress at the interface will be lower than initial peak stress at the first load application. The progressive crushing of the core will thus stop. If one now increases the fatigue load, the stress at the interface increases and the crushing process will start again. How many cycles that will take depends on the load increase. But, as before, once the crushed zone has increased in size, the stress at the interface decreases and the crushing will stop again, but at an increased crushed zone.

4 Materials

Sandwich beams were manufactured from Divinycell and Rohacell foam core [3,4]. The face sheet laminates used were made from glass-fibre NCF fabrics of the type DBLT. This is a quadriaxial non-crimp fabric (NCF) with approximately equal amount of fibres, approximately 200 g/m^2, in four main directions in the sequence [0/45/90/-45]. The laminates were manufactured using a vacuum infusion process with Reichhold DION 9500 Vinylester. A single layer of DBLT-850 builds approximately 0.75 mm after infusion. Material data for the lamina used to create input data for the simulations are given in Table 1.

Quasi-static compression tests of the foams in the thickness direction were performed using rectangular blocks of foam to provide necessary input data for the numerical analysis. The measured stress-strain responses for quasi-static compression are shown in Fig.3. The measured stress-strain relations for the cores were simplified to a tri-linear relationship, as shown in Fig.3. The yield stress was taken the stress just after the initial stress peak, i.e. disregarding the initial stress peak. The Young's modulus was taken as the ratio of the yield stress divided by the yield strain and not as the initial slope of the stress-strain relation. The results are given in Table 2.

Fatigue testing in compression was performed previously by the authors and are taken from [2]. The stress-life relations are given in Fig.4.

5 Numerical modeling

The test set-up was modeled in FEM using ABAQUS-Standard [5]. The model was in 2D with plane strain elements (bilinear plane strain quadrilateral CPE3). Several meshes where tried out with different mesh density. The face sheets were modeled with either 1 or 3 elements through the thickness. For the core a structured mesh was used with dimensions 0.5 by 1.5 mm or 1.5 by 4 mm. The reason for using non-quadratic elements was that improved convergence was found by using elements that initially had larger height than width. The reason is that the elements collapse when reaching the densification strain and by using initially rectangular elements implied that the collapsed elements had a better side aspect ratio than if using initially square elements. The different mesh densities resulted in almost identical results in terms of load-displacement response and size and shape of the crushed core zone.

The face sheets were modeled as linear elastic with orthotropic properties. The core was modeled using the built-in crushable foam model in ABAQUS. Both isotropic hardening and volumetric hardening was tried but resulted in almost identical results. Tabulated hardening was used with a linear elastic regime, followed by a plateau regime with very little hardening up until densification using the input data as given in Table 2.

The models were run using large displacement (kinematically non-linear analysis) with a forced step length of 0.01 enforcing at least 100 load steps in each analysis. These analyses were then used for several purposes. One was to calibrate the model with static indentation experiments to compare the load-displacement response and another to compare size and shape of the crushed core zone as function of indentation depth.

6 Testing procedure

The sandwich beams were placed on a solid foundation in the testing machine. The ends were clamped down to hold the specimen in place. The same set-up and boundary conditions were used in the numerical model. A photo of the test set-up is shown in Fig.5.

Quasi-static indentation tests were performed in an Instron Universal testing machine. The side of the specimen was monitored using a Digital Image Correlation (DIC) system from which full-field strains were measured.

The fatigue testing was performed with the same boundary conditions. All fatigue tests were performed in a 100 kN servohydraulic testing machine. A constant amplitude sinusoidial loading was applied to the indentor at a load ratio of 0.1 (max load/min load) and a loading frequency of 5 Hz.

The testing scheme was as follows; the fatigue testing was started with a maximum load corresponding to a quasi-static load just above the point where the core would start crushing if it was a quasi-static test. It was then run a large number of load cycles. Then the test was stopped, a quasi-static indentation performed which was monitored using the DIC-system and the size and shape of the crushed core zone was measured. The test was then re-started at a higher load, run for a large number of cycles, stopped, a new DIC-measurement, and so on.

7 Results

The first experiment consists of a beam with H100 core and 1.5 mm thick face sheets.
Figure 6 shows the load-displacement relations from these quasi-static indentation tests compared to the FE-simulation. As seen, the correlation is very good. The correlation was equally good for the other configurations.
Figure 7 shows the comparison in terms of crushed core zone size. What is shown in the zone in which the strains are plastic and another zone where the core has reached the densification strain. Again, the correlation between experiments and simulations are excellent.
The fatigue loading was started at P = 35 N/mm. In the first load cycle this load would create a small crushed core zone of the same size as in the quasi-static experiment. However, for a large number of load cycles the crushed core zone will increase in size but eventually stop growing. The size of this crushed core zone corresponds to a higher quasi-static load. If one goes back to the compression-compression fatigue results in [2] (see Fig.4) the difference between the crush strength at quasi-static load (which is 1.9 MPa for H100) and the crush strength at e.g. 10^6 load cycles (which 1.35 MPa), the ratio is 1.4. Thus, we would expect that the crush core zone size at 10^6 load cycles at 35 N/mm would be the same as for a quasi-static load of 35×1.4 = 49 N/mm.
In Fig.8 the FE-modell and quasi-static indentation results for P = 49 N/mm are shown together with the measured crush core zone after 10^6 load cycles at P = 35 N/mm.
After the measurement the fatigue loading was continued, first at 45 N/mm and then at 60 N/mm. By using the same argumentation, the cycling at these load levels at 10^6 or more load cycles would correspond to quasi-statically created crush core zones corresponding to 63 and 84 N/mm, respectively. The results for this are also shown in Fig.8.

8 Conclusions

Fatigue testing of foam core sandwich beams under localized loads have been performed. It is seen that the crush core zone grows under fatigue loading to a size which corresponds to higher quasi-static load and that this can be predicted using fatigue life data for the core extracted under compression fatigue.

9 Acknowledgements

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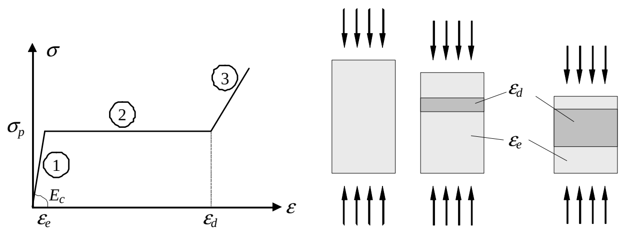

Fig.1. (a) Schematic compressive stress-strain behaviour of foams and (b) progressive layer-by-layer crushing during increased compressive strain.

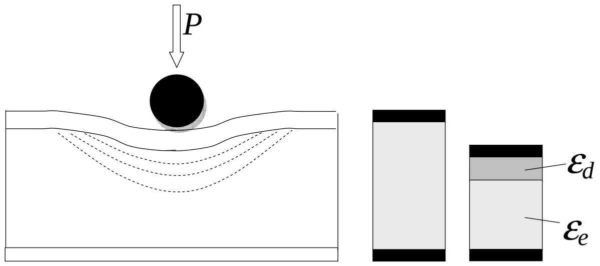

Fig.2. Model of progressive crushing during indentation load application

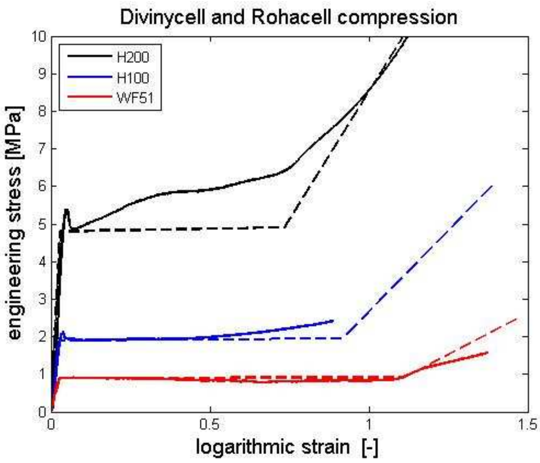

Figure 3 Typical stress-strain relations for WF51, H100 and H200. Dotted lines represent used tabulated hardening data for ABAQUS analyses.

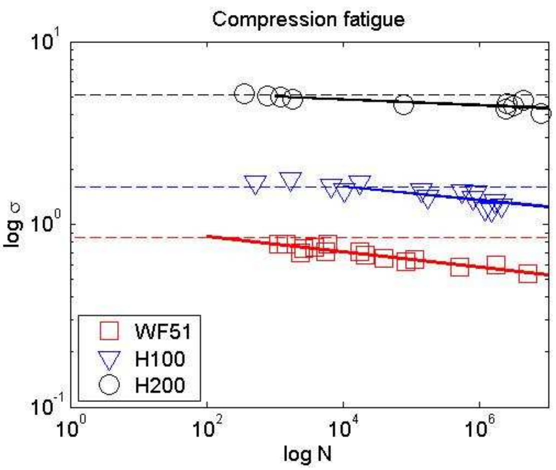

Figure 4 Stress-life curves for WF51, H100 and H200 (reproduced from [1]).

Figure 5 Photograph of experimental set-up.

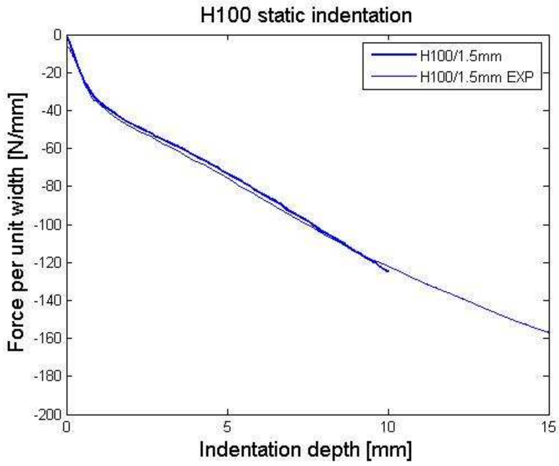

Figure 6 Load-displacement relation for quasi-static experiments

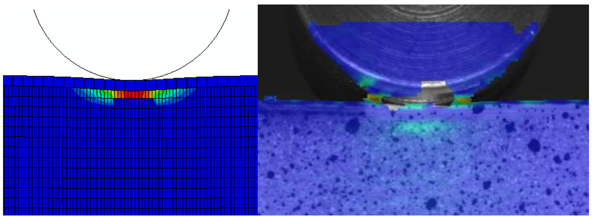

Figure 7 Comparison between experiments and simulation of the H100-beam type under quasi-static loading at P = 35 N/mm.

E_1 [GPa]	E_2 [GPa]	E_3 [GPa]	G_{12} [GPa]	G_{13} [GPa]	G_{23} [GPa]	ν_{12} [-]	ν_{13} [-]	ν_{23} [-]
31.5	7	7	3	4	3	0.25	0.25	0.25

Table 1 Material data for face sheet layers.

	E [MPa]	Yield stress [MPa]	Stress at densification strain [MPa]	Densification strain [-]*
WF51	35	–0.9	–0.9	–1.08
H100	80	–1.9	–1.95	–0.90
H200	165	–4.8	–4.9	–0.70

* Logarithmic strain as input to ABAQUS

Table 2 Compression data for the core materials used.

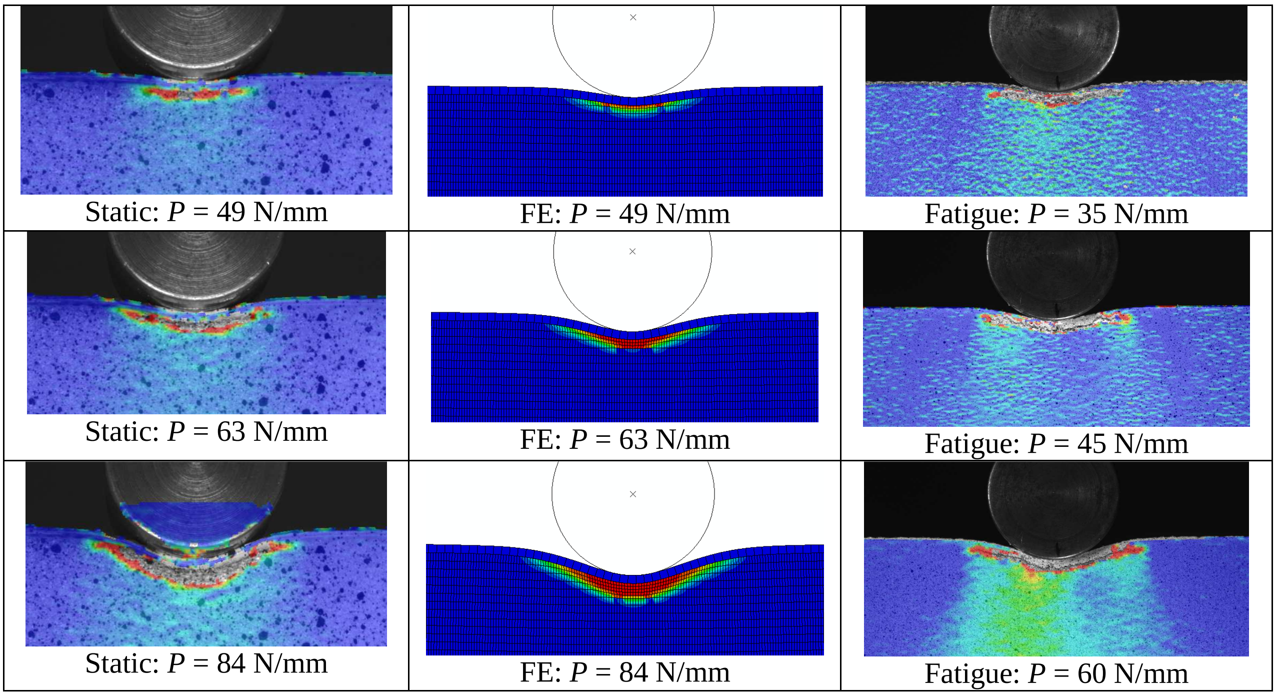

Figure 8 Crush core zone sizes in FE-simulations and quasi-static indentation tests at 49, 63, and 84 N/mm compared with measured crush core sizes after 10^6 load cycles (or more) at 35, 45, and 60 N/mm.