STATIC AND CYCLIC DAMAGE BEHAVIOR OF A CELLULAR COMPOSITE AND ITS APPLICATION IN A SANDWICH STRUCTURE

S. Diel[1] and O. Huber[2]

[1]Audi AG, Ingolstadt, Germany
[2]Competence Center for Lightweight Design, Department of Mechanical Engineering,
University of Applied Sciences Landshut, Germany
Email: otto.huber@haw-landshut.de, Web page: http://www.kompetenzzentrum-leichtbau.de

Keywords: cellular composite, syntactic foam, sandwich structure, fatigue damage modeling, frequency effect, mean stress dependency

Abstract

The design and validation of a sandwich skateboard is presented. The skateboard consists of carbon fiber reinforced face layers and a cellular composite core made from glass foam granules embedded in an epoxy resin matrix. The infiltration core composed of glass foam granules and the fiber reinforced face layers are infiltrated in one single step. Compared to skateboards made from wood, a weight reduction of 14 % and an increase of static strength by 79 % are achieved while maintaining similar stiffness. As a basis for the lifetime prediction of the core material a continuum damage mechanics model for uniaxial static and cyclic loading is developed. The damage is separated into pure static and pure fatigue damage and described in terms of stiffness loss of the material. The analysis of the cyclic fatigue includes different amplitudes, mean stresses, and load sequences. The damage evolution is modeled as a superposition of static and cyclic damage. The model incorporates nonlinear accumulation and interaction of damage. The calculated lifetimes are in good agreement with experiments.

1. Introduction

Cellular composites belong to the group of syntactic foams and use cellular granules as placeholders. The placeholders consist of glass, mineral or metal foams [1, 2]. The mechanical properties of cellular composites, such as strength or stiffness can be improved by using cellular placeholders compared to conventional cellular solids with equal weight [1, 3, 4]. The static and fatigue behavior of the presented cellular composite is analyzed in [4-6]. The application as supporting core in thin-walled members is shown in [7, 8]. The present paper covers the application of a cellular composite in a sandwich structure. Since sandwich structures are loaded by different load-time-functions, the static and cyclic damage behavior of the cellular composite is analyzed and modeled for different amplitudes, mean stresses and frequencies.

2. Application in a Sandwich Structure

Using cellular composites as core material, it is possible to produce sandwich structures with fiber-reinforced composites as face layers in one step [9, 10]. The idea is to eliminate the adhesive lamination process between core and the surface layers by integrating the surface layer production into the manufacturing process of the core. To demonstrate the advantages of the proposed cast process a 3D shaped sandwich skateboard with a cellular composite core has been developed [11]. The aim was to increase the strength and to reduce the weight compared to conventional skateboards made of plywood. The stiffness should remain similar to conventional skateboards. A cellular composite with

Excerpt from ISBN 978-3-00-053387-7

0.5–1 mm foam granules made from recycled glass was chosen as core material and carbon fiber reinforced layers are chosen as face material [6].

Due to the complex structure of the skateboard, the manufacturing process is carried out with the help of an infiltration core as proposed in [9]. The glass foam granules are coated with a small amount of epoxy resin with a mixing ratio of 5:1. After filling and curing in a core mold, a high porous infiltration core with sufficient shape stability is produced. In a following step, the infiltration core is positioned together with the dry fiber fabric into the casting mold. After closing the mold, the core and layer area are infiltrated with epoxy resin simultaneously. This leads to a homogeneous connection between the core and the faces. The advantage of this process is the ability to produce single or multiple curved structures and to avoid a separate bonding of the faces with the sandwich core.

The numerical simulation, optimization and the face lay-up of the 3D-shaped skateboard is described in [11, 12]. The optimized core and face thickness of 3.1 mm and 1.3 mm lead to a total sandwich thickness of 5.7 mm (Fig. 1a). As a result from the analytical and the numerical optimization, the weight of the sandwich skateboard could be reduced by 14 % compared to a conventional skateboard made of plywood [11, 12]. The sandwich skateboard (Fig. 1b) has a weight of 945 g (without axes and wheels).

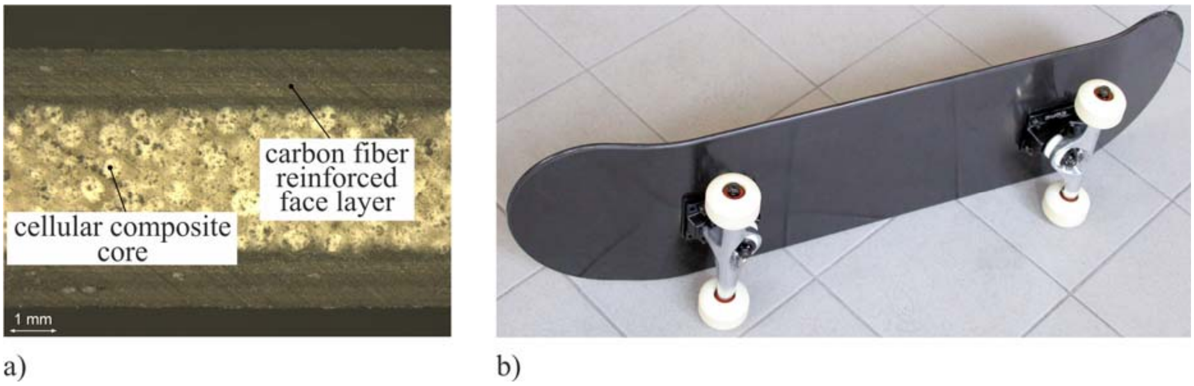
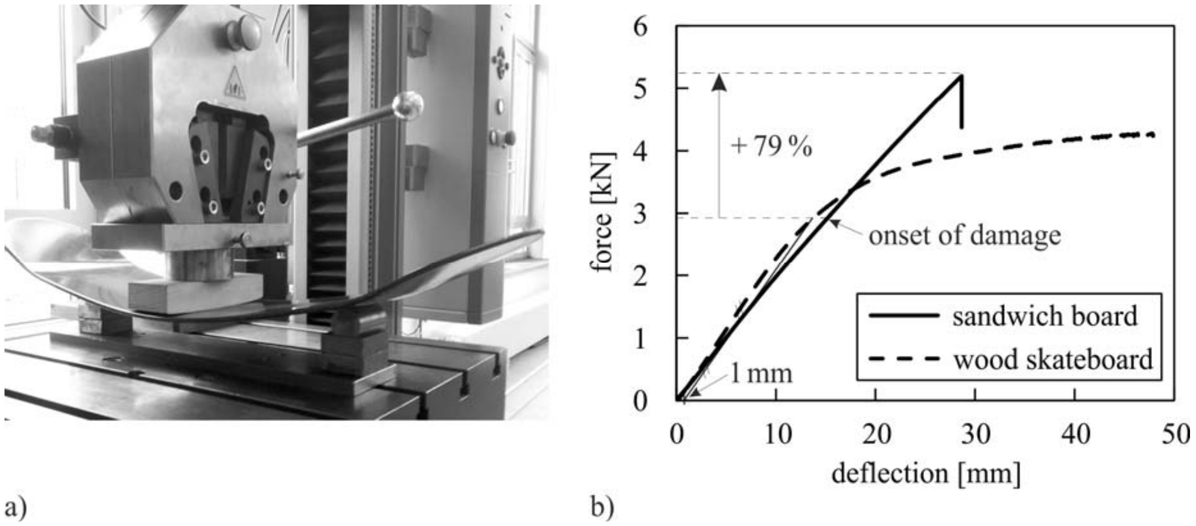


Figure 1. a) Cross section of the sandwich structure; b) Sandwich skateboard with axes and wheels

Using a 3-point bending test, the stiffness and the strength of the sandwich skateboard in comparison to a plywood skateboard are analyzed and presented in Fig. 2. The skateboard is fixed on cylindrical supports with a radius of 17.5 mm and a length of 60 mm (Fig. 2a). The support distance is 410 mm. The loading at the center is realized with a beech wood stamp, which has a width of 64 mm. The stiffness of the sandwich skateboard is only slightly below the stiffness of the plywood board (Fig. 2b). The force-deflection curve of the sandwich board remains nearly linear till fracture occurs at 5.2 kN. The plywood board shows a considerable inelastic behavior after the proportionality limit at 2.9 kN, where 1 mm inelastic deflection and the onset of damage is reached. With this criterion the strength of the sandwich skateboard is 79 % higher than the strength of the wood skateboard. The specific strength F_P/F_S (load at inelastic deflection of 1 mm divided by the structural weight) of the sandwich board is 109 % higher compared to the specific strength of the plywood board.

Excerpt from ISBN 978-3-00-053387-7



a) b)

Figure 2. a) 3-point bending on sandwich skateboard; b) Comparison of the force-deflection curves

3. Fatigue Damage Behavior of a Cellular Composite

3.1. Experimental Investigations

The quasi-static mechanical properties of cellular composites with different glass foam granule sizes were discussed in [4, 6]. Table 1 contains the mechanical properties of the cellular composite with 1-2 mm glass foam granules as used in the following investigation.

Table 1: Mechanical properties of the cellular composite with 1-2 mm glass foam granules [13]

Density ρ [g/cm³]	Young's modulus E [MPa]	Poisson's ratio ν [-]	Tensile yield strength σ_{yT} [MPa]	Tensile strength σ_{uT} [MPa]	Compressive yield strength σ_{yC} [MPa]	Compressive strength σ_{uC} [MPa]
0.72	3100	0.31	5.8	9.1	17.1	18.3

The fatigue behavior of cellular composites under static and cyclic tensile and compressive loading was investigated in [4, 5, 13]. The damage behavior was analyzed by means of scanning electron microscopy (SEM). It was found that microcracks are forming first in the glass foam granules. Subsequently, these microcracks lead to the formation of a macrocrack passing through the glass foam granules and the matrix. Macrocracks finally causes the specimen's failure. The fatigue process was found to be an interaction between the static and the cyclic damage. The damage D is described in terms of macroscopic stiffness loss (see e.g. [14])

$$D = 1 - \frac{E}{E_0}, \tag{1}$$

with the current Young's modulus E, which is defined as the initial stiffness of the unloading path of the hysteresis loop. E_0 is the initial Young's modulus of the undamaged specimen. The damage evolution in tension was found to be significantly different than in compression [5].

Excerpt from ISBN 978-3-00-053387-7

3.2. Damage Modeling

Continuum damage mechanics models for static and cyclic damage are used to model the damage evolution of the cellular composite. For calibrating the model parameters, pure static and pure cyclic damage tests were performed [13].

3.2.1. Static Damage

For the description of the static damage increment dD_s the Kachanov-Rabotnov creep damage model [15, 16]

$$\mathrm{d}D_\mathrm{s} = A\frac{\sigma^\mathrm{m}}{(1-D)^\mathrm{p}}\mathrm{d}t \tag{2}$$

with the material constants A, m and the damage exponent p is applied. The damage increment dD_s depends on the current damage D, which leads to a nonlinear damage evolution. Since p depends on the stress, it is further possible to describe nonlinear damage accumulation (sequence effects). The parameters of the static damage model and their determination are described in [13].

3.2.2. Cyclic Damage

The cyclic fatigue damage model from Chaboche and Lesne [17] is used for the description of the cyclic damage. In this model, the damage increment dD_c is calculated as function of the current damage D, stress amplitude σ_a, mean stress σ_m, stress exponent β, damage exponent α and the parameter M for the mean stress dependency by

$$\mathrm{d}D_\mathrm{c} = D^\alpha\left(\frac{\sigma_\mathrm{a}}{M}\right)^\beta \mathrm{d}N\,. \tag{3}$$

Since the damage increment dD_c depends on the current damage D it is possible to describe nonlinear damage evolution. Furthermore, it is possible to consider nonlinear damage accumulation (sequence effects) by using the damage exponent α, which depends on the load level. The parameter M for the mean stress dependency is calculated using the function $M = M_0 \cdot \sigma_A$, where M_0 is a constant. See [13] for all parameters of the cyclic damage model.

Figure 3 shows the experimentally determined fatigue limit σ_A for $N = 5 \times 10^6$ cycles depending on the mean stress σ_m. The dot-dashed lines show the linear relation between the mean stress σ_m and the stress amplitude σ_a for a constant stress ratio $R = \sigma_{min}/\sigma_{max}$. The maximum value of $\sigma_A = 6.3$ MPa is found at $\sigma_m = -4.6$ MPa. The damage and the failure behavior can be divided in a compressive and a tensile range. The failure behavior at stresses $\sigma_m < -4.6$ MPa is characterized by a progressive shortening of specimens and developing a shear band at approximately 45° to the loading axis [4]. In contrast to compression, the strain development in tension is low and the specimens fail by a macrocrack propagation through the matrix and the glass foam granules normal to the loading direction. This kind of damage and failure is typical for brittle materials.

In the original version of the cyclic damage model, a linear dependency (Goodman relation) between the mean stress and the fatigue limit is used [17]. It can be seen in Fig. 3 that this approach cannot be used in case of the investigated cellular composite. Therefore, the fatigue limit is approximated using the Gaussian distribution

$$\sigma_\mathrm{A} = \frac{55(\mathrm{MPa})^2}{\sqrt{2\pi}\cdot 3.6\,\mathrm{MPa}}\,e^{-\frac{1}{2}\frac{(\sigma_\mathrm{m}-(-4.6\,\mathrm{MPa}))^2}{(3.6\,\mathrm{MPa})^2}} \tag{4}$$

Excerpt from ISBN 978-3-00-053387-7

in the present work. The Gaussian distribution is often used in case of fiber reinforced plastics, see e.g. [18].

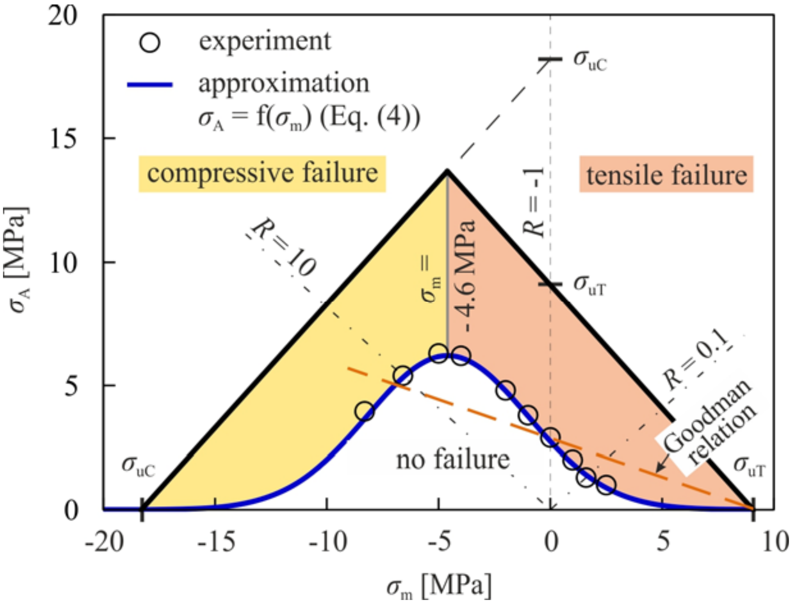


Figure 3. Fatigue limit σ_A for $N = 5 \times 10^6$ cycles under mean stress σ_m

3.2.3. Damage Interaction

In case of the investigated cellular composite, the static and cyclic damage lead to the microcrack growth in the glass foam granules in the same way [4, 5, 13]. Both types of damage can interact and accelerate the damage process. In this case, the total damage increment can be computed as sum of the static and cyclic damage increments [19] with

$$\mathrm{d}D = \mathrm{d}D_S + \mathrm{d}D_C \,. \tag{5}$$

Using this procedure it is possible to account for nonlinear damage accumulation and interaction between the static and the cyclic damage [19]. The integration of Eq. 5 is performed numerically using an explicit Euler code. A cycle jumping procedure was developed, which allows for a fast calculation of damage evolution for arbitrary load frequencies [13].

4. Lifetime Calculation and Comparison with Experiment

To demonstrate the capability of the damage model, the lifetimes for compressive cyclic loading (R = 10) and different frequencies are calculated and compared with experimental results. In the present case, a sine waveform is used. Experimental results are available for 0.1 Hz, 1 Hz and 20 Hz test frequency. Figure 4 shows that there is a strong influence of frequency on the lifetime in terms of number of cycles to failure N_f. The lifetime at higher frequencies is higher than that at lower frequencies because the cumulative time at load for static damage is shorter.

The results obtained from the damage model agree well with the experimental results, see Fig. 4. It can be seen that N_f is continuously decreasing by reducing the test frequency because the static damage is gaining more influence. In contrast, the calculated fatigue life for 100 Hz test frequency is only slightly higher than that at 20 Hz test frequency. This means that the influence of static damage

Excerpt from ISBN 978-3-00-053387-7

becomes lower at higher frequencies. Further results including an investigation of different load ratios, sequence effects and signal form influence are discussed in [13].

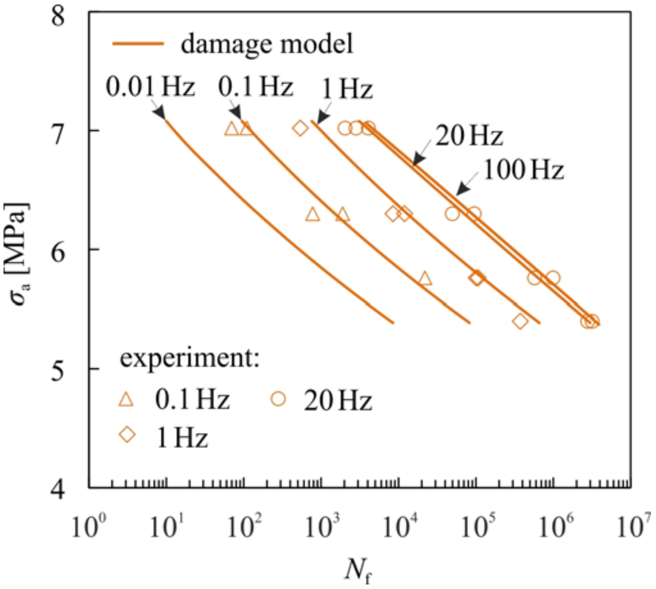


Figure 4. Effect of loading frequency in case of compressive cyclic loading (R = 10, sine waveform)

5. Conclusions

A newly developed infiltration method enables the production of complex 3D shaped sandwich structures with cellular composites as core material and fibre reinforced composites as face layers in one step. The investigated cellular composite is an epoxy resin based syntactic foam reinforced with glass foam granules made from recycled glass. As an example, a lightweight sandwich skateboard was developed. The weight of the sandwich skateboard could be reduced by 14 % compared to a conventional skateboard made of plywood. While maintaining a similar stiffness, the static strength of the sandwich board could be increased by 79 %.

A continuum damage mechanics model for cellular composites under static and cyclic loading is presented. The damage is modeled as an interaction between static and cyclic damage and the model incorporates nonlinear accumulation and interaction of damage. For this purpose, the damage is separated into pure static and pure cyclic damage and described in terms of stiffness loss of the material. The frequency effect is caused by an interaction of static and cyclic damage, which is included within the presented damage model. The mean stress dependency is analyzed experimentally and approximated by a Gaussian distribution with high accuracy. The calculated lifetimes at different loading frequencies are in good agreement with experiments.

Acknowledgment

The authors acknowledge the financial support of the German Federal Ministry of Education and Research (BMBF) within the funding program FHprofUnt in the project “LeitHyb” under the contract number 17008X11.

Excerpt from ISBN 978-3-00-053387-7

References

[1] H. Klaus, O. Huber and G. Kuhn. Lightweight potential of novel cellular spherical composites. *Advanced Engineering Materials*, 7:1117-1124, 2005.

[2] O. Huber, H. Klaus, R. Dallner, F. Bartl, K. Eigenfeld, B. Kovacs and M. Godehardt. Herstellung und Eigenschaften syntaktischer Metallschäume mit unterschiedlichen Matrix- und Füllmaterialien. *Druckguss-Praxis*, 1:19-24, 2006.

[3] H. Klaus. *Charakterisierung, Modellierung und Anwendung zellularer Verbundwerkstoffe im elasto-plastischen Bereich*. Dissertation. University of Erlangen-Nuremberg, 2007.

[4] S. Diel, O. Huber, H. Saage, P. Steinmann and W. Winter. Mechanical behavior of a cellular composite under quasi-static, static and cyclic compression loading. *Journal of Materials Science*, 47:5635-5645, 2012.

[5] S. Diel and O. Huber. Comparison of tensile and compressive creep-fatigue damage behavior of cellular composites. *Advanced Materials Research*, 891-892, p. 633-638, 2014.

[6] S. Diel and O. Huber. Cellular composites - mechanical properties and applications in sandwich structures. *Proceedings of the International Conference Cellular Materials - CELLMAT 2012*, Dresden, Germany, 2012.

[7] J. Denk, S. Diel and O. Huber. Experimental and Numerical Analyses of the Lightweight Potential for Hybrid Thin-Walled Members. *Materials Science Forum*, 825-826, p. 732-740, 2015.

[8] O. Huber and S. Diel. Leichtbau-Hybridstruktur für das Chassis von Reisemobilen (LeitHyb). *Schriftenreihe Leichtbau – Band 1*, LC-Verlag, Landshut, 2015.

[9] O. Huber and H. Klaus. Cellular composites in lightweight sandwich applications. *Materials Letters*, 63:1117-1120, 2009.

[10] O. Huber and H. Klaus. *Lightweight moulded piece and corresponding production method*. European Patent, EP 2 125 358 B1, 2014.

[11] O. Huber and S. Diel. Entwicklung hybrider Leichtbaustrukturen aus Verbundwerkstoffen und Werkstoffverbunden. In: *Kolloquienreihe Innovation und Nachhaltigkeit 2013*. Eds. H. Rapp and W. Muntzinger. Neubiberg: Universität der Bundeswehr München, Fakultät für Luft- und Raumfahrttechnik, 2014.

[12] S. Diel, F. Bürgel and O. Huber. Auslegung und Optimierung eines Skateboards in Sandwichbauweise mit zellularen Verbundwerkstoffen und integrierten faserverstärkten Deckschichten. *Proceedings of the ANSYS Conference and 30th CADFEM Users Meeting*, Kassel, Germany, 2012.

[13] S. Diel. *Charakterisierung und Modellierung des quasi-statischen Verhaltens und der Ermüdung eines zellularen Verbundwerkstoffes*. Dissertation, University of Erlangen-Nuremberg, 2015.

[14] J. Lemaitre. *A course on damage mechanics*. Springer, 1996.

[15] L. M. Kachanov. *Zeitlicher Ablauf des Bruchprozesses unter Kriechbedingungen*. Izvestiya Akademii Nauk UdSSR, 8:26-31, 1958.

[16] Y. N. Rabotnov. *Creep problems in structural members*. North-Holland, 1969.

[17] J.-L. Chaboche and P. M. Lesne. A non-linear continuous fatigue damage model. *Fatigue & Fracture of Engineering Materials & Structures*, 11:1-17, 1988.

[18] A. P. Vassilopoulos. *Fatigue life prediction of composites and composite structures*. Woodhead Publishing, 2010.

[19] J. Lemaitre and J.-L. Chaboche. A nonlinear model of creep-fatigue damage cumulation and interaction. *Proceddings of IUTAM Symposium on Mechanics of Visco-Elastic Media and Bodies*, Springer, 1975.

Excerpt from ISBN 978-3-00-053387-7