FATIGUE BEHAVIOUR OF SANDWICH FOAM CORE MATERIALS – COMPARISON OF DIFFERENT CORE MATERIALS

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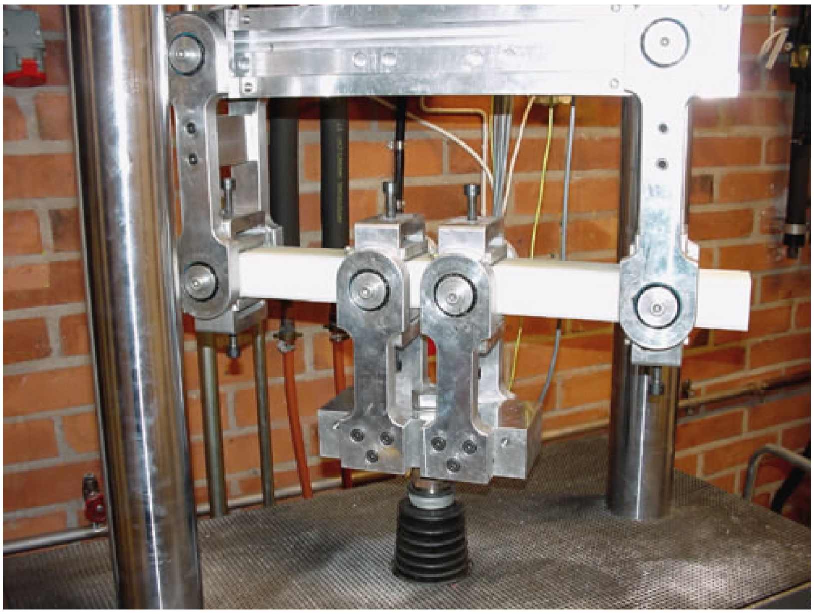
SUMMARY

Sandwich technology offers a wide range of advantages compared to monolithic construction. Weight vs. stiffness is the key factor why composite sandwich technology is used in a rapidly growing number of applications.
However, long term behaviour of sandwich constructions is a major concern for dynamically loaded applications such as railcars, high speed marine vessels, aerospace applications and wind turbine blades.

The paper describes and concludes a test series, carried out at the Royal Institute of Technology KTH in Stockholm where X-PVC, PEI and PMI cored sandwich beams were fatigue tested in a four-point bending test rig. Fracture loads, displacements, shear strengths and S/N diagrams of the aforementioned sandwich beams have been determined. Loads were chosen to achieve fatigue fracture between 1000 and 5 million load cycles. After 5 million cycles the specimens were tested for the residual shear strength using static testing according ASTM C393-62.



Picture 1: Set-up for fatigue shear testing at KTH Stockholm

INTRODUCTION

Fatigue properties are investigated for PMI, X-PVC and PEI structural foams. Different densities are tested as core materials in sandwich beams. All tests are performed in a four point bending rig which design is chosen as to induce a core shear failure. Quasi-static testing for the shear strengths is firstly performed. Loads were chosen to achieve fatigue fracture between 1000 and 5 million load cycles. The test results are presented in a S/N diagram where the fatigue loads are given as percentage of the shear strength. Specimens that had not failed after 5 million cycles are tested for the residual strength using the same procedure as for the quasi-static testing initially performed.

TEST METHOD

All tests have been performed using a four point bending test rig. The test procedure used is based on the standard test method ASTM C393-62 [1]. This standard test method only considers static testing. An extension of the four-point bending procedure to fatigue testing has been proposed [2] and used with success in several investigations of the fatigue life of shear loaded foam core materials [3-4]. The inherent advantages of the four-point bend test are that no large stress concentrations are present and that the entire assembly (face - adhesive joint - core) is loaded in a representative way i.e. as in an application of a real sandwich structure. Bending moment and transverse force diagrams are shown in Fig. 1 where it is seen that the transverse force is constant between the inner and outer supports while the bending moment decreases from its maximum between the inner supports to zero at the outer supports. Hence, the feature of the four-point bending test is that in the middle section the bending moment is constant (and of maximum) with zero transverse force and in the regimes between the outer and inner supports the transverse force is constant.

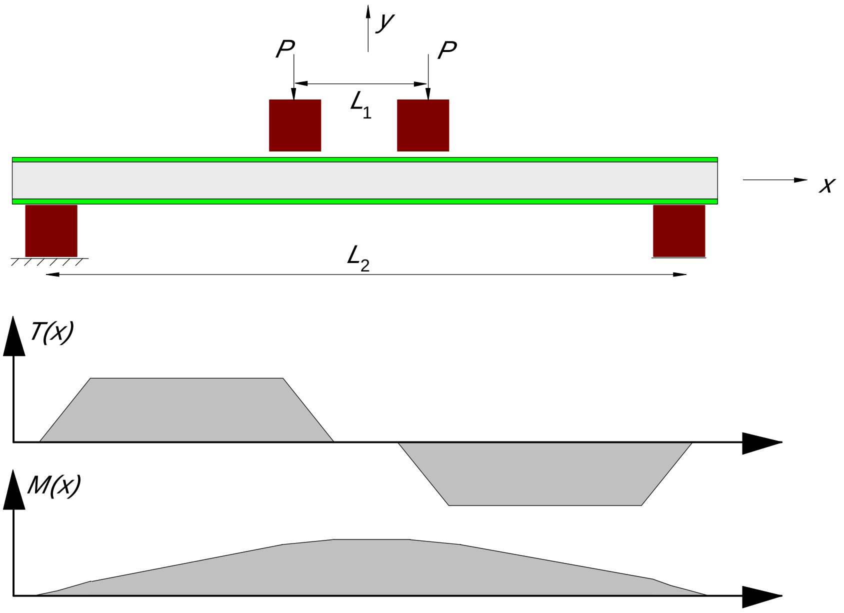


Figure 1. The four point bending set-up with idealised transverse force and bending moment diagrams.

This test method provides an almost pure shear stress in the core, between the inner and outer supports, and is hence very suitable for the present purposes.

The maximum transverse force, T, and thus also the maximum shear stress, $\tau_{\max}$, in the core in this configuration is found using the approximate relation as described in standard textbooks, e.g. Zenkert [5] for the core shear stress

$$|T|_{\max} = P \text{ and } \tau_{\max} = \frac{P}{t_c + t_f} \tag{1}$$

where P is half the applied load in the four point bending rig, t_c and t_f are the core and face thickness respectively. Similarly, the maximum bending moment, $M_{\max}$, and thus the maximum face tensile/compressive stress (for a sandwich with equal faces) is found by using the approximate relation for the face stress

$$|M|_{\max} = \frac{P(L_2 - L_1)}{2} \text{ and } \sigma_{\max} = \frac{P(L_2 - L_1)}{2t_f d} \tag{2}$$

where L_1 and L_2 are the distances between the supports as illustrated in figure 1. In order to design the four-point bending specimen to ensure core shear failure, the support distances must be calculated so that core shear becomes critical. Assuming the core has an ultimate shear strength $\hat{\tau}_c$ and the face has a critical tensile strength $\hat{\sigma}_f$, where the latter can be either a compressive, a tensile or a local buckling strength, the local buckling, or wrinkling strength, is estimated using the relation between the face and core elastic modulus, E_f and E_c and of the core shear modulus as

$$\hat{\sigma}_{lb} = \frac{1}{2}\sqrt[3]{E_f E_c G_c} \tag{3}$$

SPECIMEN

The sandwich configuration was chosen from a typical marine application and therefore the manufacturing process chosen accordingly. The sandwich is made up in one step where the faces are manufactured using an infusing technique directly onto the core material. The dry fibres are laid up directly on both sides on the large core sheets, a resin distribution media and vacuum film is the added on top and sealed. Vacuum is then applied and the resin fed through an inlet. Both faces are hence impregnated at the same time. The manufacturing and the curing process took place at room temperature and was carried out by FLYG, KTH. The specimens were then cut to correct size using a diamond coated circular saw. The geometry and the properties of the specimen are given in tables 1 and 2. The mechanical properties of the different core materials are given in Table 7.

Configuration	Face	Face thickness [mm]	Core	Core thickness, t_c [mm]	Core width, b [mm]
I	Glass/Vinylester	3.7	PMI 51 S	40	40
II	Glass/Vinylester	3.7	PMI 71 IG	40	40
III	Glass/Vinylester	3.7	PMI 71 FX	40	40
IV	Glass/Vinylester	3.7	PMI 71 WF	40	40
V	Glass/Vinylester	3.7	X-PVC 80	40	40
VI	Glass/Vinylester	3.7	X-PVC 60	40	40
VII	Glass/Vinylester	3.7	PEI 80	40	40

Table 1. Material combinations used

Face material Property	DBL-800/8084 $[0°/-45°/+45°]_{2s}$
E_1 [GPa]	20.1
G_{12} [GPa]	*2.0*
Thickness (mm)	3.7

Table 2. Face material properties

STATIC SHEAR TESTS

Static tests were initially performed to get relevant load levels for the fatigue tests. Three identical specimens within each configuration were tested at room temperature, 22°C, in a Schenk PSA40 hydraulic testing machine at a constant displacement rate of 6 mm/min according to ASTM C393-62.

Core	Fracture load, $2P$ [kN]	Fracture Dis placement [mm]	Fracture Shear strength [MPa]
PMI 51 S	2.96	9.2	0.69
PMI 71 IG	6.64	11.1	1.54
PMI 71 FX	2.57	29.2	0.60
PMI 71 WF	6,39	12,8	2,0
X-PVC 80	4,55	26,0	1,42
X-PVC 60	3,28	19,4	1,03
PEI 80	4,44	30,0	1,39

Table 3. Static failure load and material shear strength according to ASTM C393-62

FATIGUE TESTING

The main objectives within this investigation were to obtain basic knowledge on the fatigue behaviour of these foam materials and a scheme using constant amplitude loading was used. The tests were performed at the loading ratio R=0.1. A minimum of 6 specimens within each configuration and stress ratio was used.

Fatigue tests were performed in a 40 kN Schenk servo hydraulic universal testing machine. A special type of control loop was used through out all fatigue tests - the indirect load control. The tests are conducted in displacement control but the response from the load cell is registered and after a specified number of cycles an average of the load deviation is fed back to the displacement control. This process has earlier successfully been used for tests at low load levels, or rather in the lower range of the load cell capacity or in the cases where the test rig is heavy which also effects the control adversely.

The fatigue results are presented as standard *S/N* diagrams in e.g. Fig. 2 for PMI 51 S with the load normalised with respect to the static failure load. The number of cycles n is plotted on the *x*-axis on a logarithmic scale. The maximum number of load cycles was set to 5 million, and hence some tests were interrupted at this point without any indication of failure. Picture 2 shows a typical fatigue fracture for e.g. PMI 51 S at P/P_{crit}=65%, n=$1.1 \cdot 10^6$ cycles. In Figure 3 –5 the S/N diagrams for X-PVC and PEI. Table 4 shows the results from the fatigue tests after $5 \cdot 10^6$ Cycles.

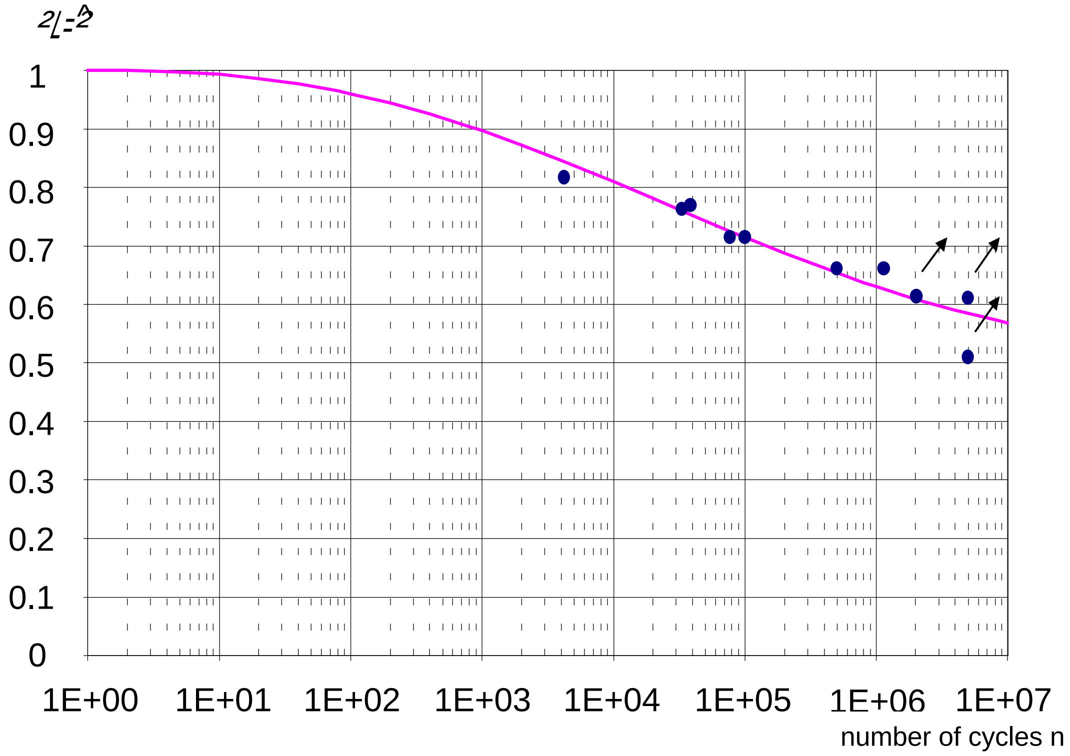


Figure 2. *S/N* diagram for PMI 51 S beams with curve fits using Eq. (4).

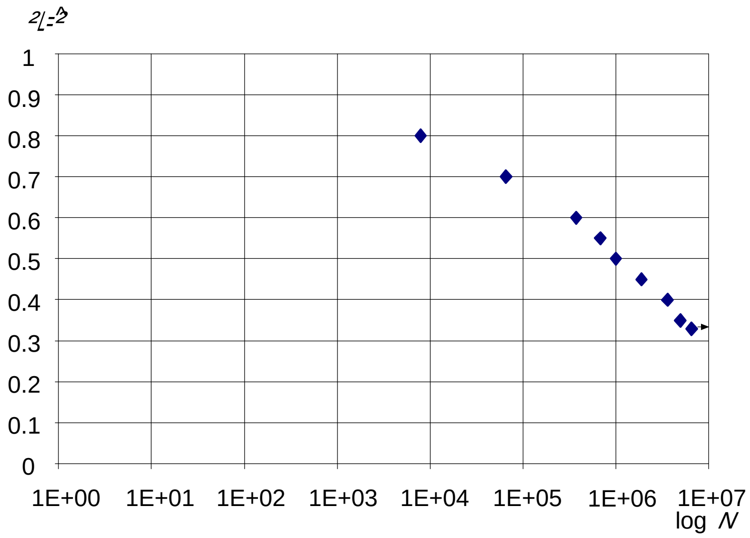


Figure 3. *S/N* diagram for X-PVC 80 beams

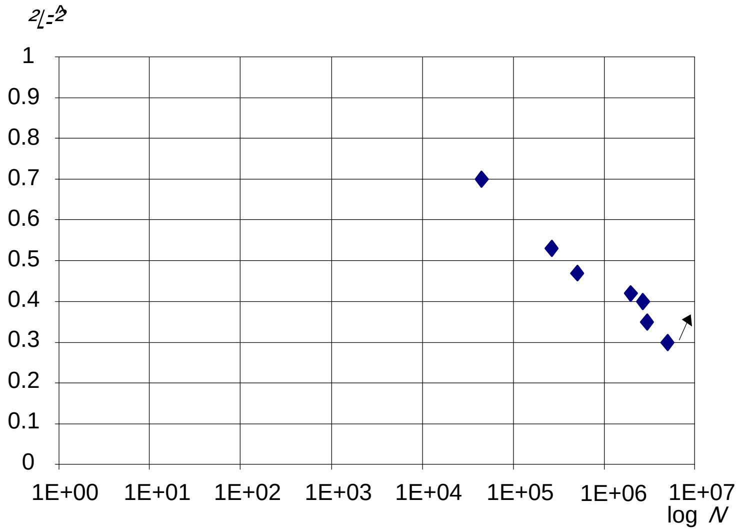


Figure 4. *S/N* diagram for X-PVC 60 beams

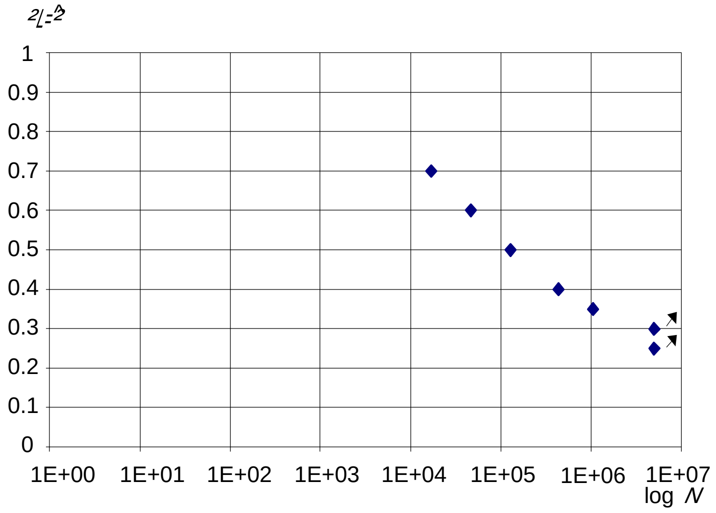


Figure 5. *S/N* diagram for PEI 80 beams.

Picture 2: Fatigue fracture of PMI 51 S, P/P_{crit}=65%, n=1.1·10^6 cycles

	PMI 51S	PMI71IG	PMI 71FX	PMI71WF	X-PVC 80	X-PVC 60	PEI 80
τ / τ_{crit}	0,58	0,52	0,52	0,5	0,33	0,3	0,25
F (Hz)	4	4	4	4	4	4	3

Table 4: Results from fatigue tests after 5·10^6 Cycles

RESIDUAL SHEAR STRENGTH

The fatigue testing was interrupted if a specimen had not failed at 5 million cycles. These specimens were instead brought to fracture under a quasi-static loading. The testing procedure was identical as in the quasi-static testing initially performed. The results are given in table 5.

Core	Fatigue load, 2*P* [kN]	Fracture load, 2*P* [kN]	Fracture Dis placement [mm]	Fracture Shear strength [MPa]
PMI 51 S	1.81	2.87	9.1	0.67
PMI 71 IG	3.33	5.95	10.6	1.38
PMI 71FX	1.30	2.67	30.8	0.62
PMI 71WF	3,19	5,94	10,9	1,86
X-PVC 80	1,45	4,31	11,0	1,35
X-PVC 60	0,99	3,31	15,5	1,03
PEI 80	1,29	4,16	12,9	1,3

Table 5. Residual shear strength of sandwich beams loaded in fatigue for 5·10^6 cycles without failure. The second column state the maximum fatigue load applied.

CONCLUSION

The performed test series showed that PMI foams can be loaded up to 58% of their static fracture load. X-PVC can be loaded up to 33% of its static fracture load and PEI foam up to 25%. The PMI cores showed the highest endurance limit for fatigue behaviour (see Table 4).

The fracture load and the fracture shear strength differs only in a few percent from the values before the fatigue testing. This underlines the good reliability of PMI foams in dynamically loaded demanding sandwich constructions.

The fracture displacement of PVC and PEI after 5 million cycles reduces by up to 57%. The foam cores lost their initially ductile behaviour. For further investigations this phenomenon should be deeper investigated to understand the reduction of this significant change in properties.
The fracture displacement of the fatigue tested PMI cores however remained on the same magnitude.

Core	Fracture load, $2P$ $n=0$ [kN]	Fracture load, $2P$ $n=5\cdot10^6$ [kN]	Fracture Shear strength $n=0$ [MPa]	Fracture Shear strength $n=5\cdot10^6$ [MPa]	Fracture Dis placement $n=0$ [mm]	Fracture Dis placement $n=5\cdot10^6$ [mm]
PMI 51 S	3,0	2,9	0,7	0,7	9.2	9.1
PMI 71 IG	6.6	6,0	1,5	1,4	11.1	10.6
PMI 71FX	2.6	2,7	0,6	0,6	29.2	30.8
PMI 71WF	6,4	5,9	2,0	1,9	12,8	10,9
X-PVC 80	4,6	4,3	1,4	1,4	26,0	11,0
X-PVC 60	3,3	3,3	1,0	1,0	19,4	15,5
PEI 80	4,4	4,2	1,4	1,3	30,0	12,9

Table 6: Summary of mechanical properties before and after dynamical measurement

PMI sandwich foam core materials proofed themselves suitable for high loaded applications such as railcars, high speed marine vessels, aerospace applications and wind turbine blades since many years. This is clearly underlined by the results of the test series carried out.
Further investigations should be carried out to create a sufficient data base, enabling designers to identify the optimum core material for a particular application.
The same standard tests should be used to give engineers dealing with metal constructions, an easy access to the world of composites.

Core	Density [kg/m³]	Compression strength [MPa]	Shear strength [MPa]	Tensile strength [MPa]	Elongation at break [%]	Elongation at break Norm
PMI 51 S [6]	52	0,7	0,6	1,1	3,5	ISO 527-2
PMI 71 IG[6]	75	1,5	1,3	2,8	4,5	ISO 527-2
PMI 71FX[6]	75	0,8	0,7	1,5	9	ISO 527-2
PMI 71WF[6]	75	1,7	1,3	2,2	3,0	ISO 527-2
X-PVC 80 [7]	80	1,3	1,2	1,95	5	ISO 193-6
X-PVC 60 [7]	60	0,85	0,8	1,3	5	ISO 193-6
PEI 80 [7]	80	0,95	1,1	1,8	20	ISO 1922

Table 7: Prospect values of core materials

ABBREVITIONS

X-PVC	cross linked Polyvinyl Chloride
PMI	Polymethacrylimide
PEI	Polyetherimide
KTH	Kungl Tekniska Högskolan
S/N	stress versus number of cycles

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