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Short Communication: Material Properties

Dynamic fracture toughness of polyurethane foam

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ABSTRACT

This paper is a first attempt to determine the dynamic fracture toughness of polyurethane foam and to study the effect of impregnation on the fracture toughness. Instrumented impact tests were performed using notched specimens. In order to study the effect of impregnation on the impact properties two different resins were used. The obtained results show that the impregnation increases the dynamic fracture toughness by 27%.

1. Introduction

Polyurethane (PUR) foam materials are widely used as cores in sandwich composites, for packing and cushioning. They are made of interconnected networks of solid struts and cell walls incorporating voids with entrapped gas. The main characteristics of foams are lightweight, high porosity, high crushability, and good energy absorption capacity [1]. Particularly for the design of high performance sandwich composites, a good knowledge of the behaviour of different grades of foam is necessary. Of particular interest is the fracture toughness of such foams because foam cracking weakens the structure's capacity for carrying loads. Many efforts have been made in recent years to determine the fracture toughness of different types of foam in static and dynamic loading conditions. Micromechanical models and experimental investigations were used for estimating the fracture toughness.

The first correlation between fracture toughness of PUR foams and density (<200 kg/m^3) was proposed by McIntyre and Anderson [2] in a linear form. The same behaviour was observed by Danielsson [3] on PVC Divinycell foams and Viana and Carlsson on Diab H foams [4]. A correlation between the static fracture toughness and relative density ρ/ρ_s was proposed in [1] in the form: $K_{Ic} = C\sigma_{fs}\sqrt{\pi l}(\rho/\rho_s)^m$, where σ_{fs} is the modulus of rupture of the cell wall material in bending, l is the cell dimension, C represents a constant of proportionality and m an exponent (equal with 3/2 for open cell). In Ref. [4], a value $m = 2$ for closed cell foam is used.

Kabir et al. [5] investigated the dynamic fracture toughness and found a maximum value of 2.74 MPa m$^{0.5}$ for PVC foam with 260 kg/m^3 density which is 3.75 times higher than the static fracture toughness of the same foam. They observed that fracture is brittle without yielding and is produced in Mode I. Mills and Kang [6] used a falling mass with a compact tension specimen in order to determine the dynamic fracture toughness, and Mills [7] also proposed a correlation between the dynamic fracture toughness and foam density. However, the dynamic fracture toughness for PUR foams has not been reported in the literature. On the other hand, the effect of impregnation on mechanical properties of foams was pointed out by Apostol et al. [8] but is less studied compared with the effect of density, strain rate or temperature.

For the determination of the dynamic fracture toughness of polyurethane foam an instrumented impact test was considered. A 200 kg/m^3 density rigid foam was used in the experimental program. The foam was impregnated

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Table 1
Comparison of static characteristics for polyurethane foams

Foam type		Tested			Divinycell
Properties	Units	Un-impreg.	Polyester impreg.	Epoxy impreg.	H200 [11]
Density	kg/m^3	200	200	200	200
Compressive strength	MPa	5.07	4.97	4.95	4.5
Compressive modulus	MPa	113	131.3	132.7	150
Tensile strength	MPa	5.39	5.12	4.05	4.8
Tensile modulus	MPa	169.3	191.4	259.4	210
Flexural strength	MPa	6.84	6.66	6.91	n.a.
Flexural modulus	MPa	146	211.8	294.5	n.a.

with polyester and epoxy resins and a study of impregnation on the impact energy and fracture toughness was performed.

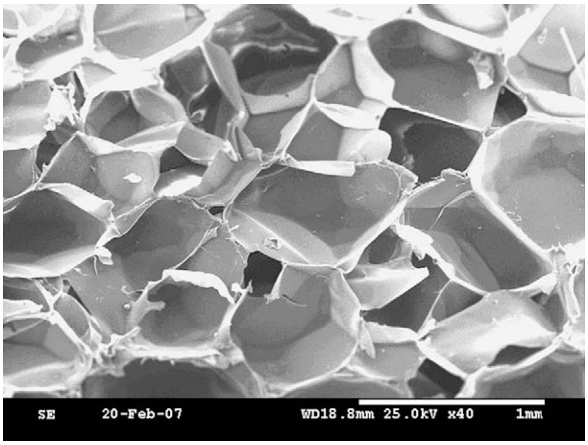

Fig. 1. The microstructure of PUR foam.

2. Test methodology

The investigated material is a 200 kg/m^3 closed cell polyurethane (PUR) rigid foam. The foam faces were impregnated with epoxy (layer of 170 μm) and polyester (layer of 100 μm) resin in order to increase durability of the foam used for lightweight boats. The foam was manufactured and supplied in the form of flat panels of 12 mm thickness. The microscopic structure of the foam is presented in Fig. 1, and the characteristic dimensions are cell – wall size 200–500 μm and wall thickness 3–4 μm. The main mechanical characteristics of the investigated foam were determined experimentally [9,10] and are summarised in Table 1 side by side with the same characteristics of commercial Divinycell foam of the same density [11]. From Table 1 it can be observed that the impregnation layer has no effect on the tensile and flexural strength but has important influence on the tensile and flexural modulus [9].

The results of the impact test on this type of foam on unnotched specimens show that the impregnation layer decreases the energy absorbed to fracture [10].

Three point bend specimens (12 × 12 × 60 mm) were adopted with a notch of 1.5 mm (cut with a razor blade), impregnated with epoxy (0.170 mm layer thickness) and polyester (0.100 mm layer thickness) resin. A span of 40 mm was used for the test and the impact load was applied in the transverse direction.

The principle of impact and instrumented impact tests of plastic materials are given in the EN ISO 179 [12,13] and, for example, by Kalthoff [14].

A KB Pruftechnik pendulum (Germany) was used for the instrumented impact tests, with the following main characteristics: pendulum mass 2.04 kg, pendulum length 0.386 m, drop height 0.742 m, drop angle 157.32°, pendulum energy 7.5 J, impact velocity 3.815 m/s. The tup has a built-in electronic sensor which allows recording the load with 1 MHz frequency. A four-channel data acquisition A/D card (AdLink NuDAQ PCI-9812) was used for recording the load in time. Tests were performed at room temperature.

The load history $F(t)$ was recorded by using strain gages bonded near the striker edge. The displacement $s(t)$ of the specimen during the test was calculated according to [13,14]:

$$s(t) = v_0 t - \frac{L_p g}{M_H} \int_0^t \int_0^{t_1} F(t) dt \, dt_1 \quad [m] \tag{1}$$

where t is the time after impact in which the deflection is calculated [s], L_p is the pendulum length [m], M_H is the horizontal moment of the pendulum [Nm], $F(t)$ is the force measured at time t after impact [N], g is the gravitational acceleration [m/s^2].

The energy is given by:

$$W = \int_0^s F(s) ds \quad [J] \tag{2}$$

where s is the deflection [m] and F is the force in [N]. The Charpy impact strength for notched specimen a_{cU} is given by:

$$a_{cU} = \frac{W_f}{BH_N} 1000 \quad [kJ/m^2] \tag{3}$$

where B is the width of the specimen and H_N is the width remaining at the base of the notch in the specimen [mm].

The dynamic fracture toughness was calculated according to [15]:

$$K_{Id} = \frac{F_{max} S}{BH^{3/2}} f(a/H) \quad [MPa\ m^{0.5}] \tag{4}$$

where F_{max} is the maximum force, S is the span, and B and H are specimen dimensions. The function $f(a/H)$ is given by:

$$f(a/H) = 1.5\sqrt{a/H} \frac{1.99 - (a/H)(1 - a/H)\left[2.15 - 3.93(a/H) + 2.7(a/H)^2\right]}{(1 + 2a/H)(1 - a/H)^2}. \tag{5}$$