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Test method

Modelling of the strain rate dependent deformation behaviour of rigid polyurethane foams

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ABSTRACT

Rigid polymer foams exhibit excellent mechanical properties for the use in impact and crash components of lightweight structures, such as core layer of sandwich-structures. The design of these lightweight structures strongly depends on secured knowledge of the stress-strain response at various strain rates. For the purpose of predicting the strain rate dependent behaviour under compression loading, an analytical model based on a Burgers model was developed and validated with comprehensive experimental tests of a rigid closed-cell polyurethane foam with different densities (230 kg/m^3, 420 kg/m^3 and 610 kg/m^3) using a servo-hydraulic high speed testing machine at defined strain rates, ranging from 0.0004 s^{-1} to 8 s^{-1}.

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1. Introduction

Due to their excellent mechanical properties, high impact resistance and energy absorption abilities, rigid polymer foams based on polyurethane (PUR) are predestined for many applications, such as thermal insulation, packaging and as core-layer of sandwich-structures for load-bearing components [1–3]. In recent years, the lightweight potential of rigid PUR foams gained significant relevance as cellular plastics were increasingly used as matrix material with reinforcing components, such as natural [4,5] and glass fibres [6,7]. The design of these lightweight structures strongly depends on a sound knowledge of the mechanical properties and especially in the case of impact and crash components on reliable information on the strain rate dependent material behaviour.

The deformation behaviour of PUR foam can be distinguished into several stages: The linear elastic region is governed by the compression and bending of cell edges, stretching of cell faces and in the case of closed-cell foams the compression of trapped gases [1,8]. Although the tested material has a certain amount of trapped air in the closed-cell structure, depending on the specific material volume fraction, the contribution of this air to the stress in the linear region is usually considered to be very low for rigid foams. With the continued increase of loading, cell walls' buckling and plastic deformation is initiated until the foam reaches the collapsing stress whereby the material behaviour is characterized by a large strain deformation with a minimal increase in stress due to a progressive collapse of the foam material [9,10]. The stress-strain response of polymer foams has been extensively investigated, especially in uniaxial compression loading [11–14]. In most cases, the modelling was carried out by Finite-Element-Analysis (FEA) of the cellular structure or analytical models without consideration of visco-elastic and visco-plastic phenomena. Rheological models which enable the analysis of these effects are mostly used for the description of relaxation and creep processes.

The focus of this article is the modelling of the strain rate dependent deformation behaviour of rigid polyurethane foam for selected foam densities by rheological models and the determination of the material specific parameters of the constitutive equations. Analytical results are verified by comprehensive experimental investigations of compression tests under high speed loading over a wide range of strain rates.

2. Analytical model

For the modelling of the strain rate dependent deformation behaviour of thermoset plastics the Zener$_k$-model can be used. In the case of thermoset cellular polymers, which are characterized by a distinctive yielding due to the cell collapse, the Zener$_k$-model needs to be extended. In this context, the Burgers model, which combines the linear stress-strain relationship of a serial spring with the visco-elastic behaviour of a parallel spring-dashpot

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combination and the visco-plastic flow of the dashpot in series was used to predict the strain rate dependent compression behaviour of the closed-cell foam structure (Fig. 1).

The stress-strain relations of this model can be described by the differential equation.

$$\ddot{\boldsymbol{\sigma}} + \left(\frac{\boldsymbol{E}_1 + \boldsymbol{E}_2}{\boldsymbol{\eta}_1} + \frac{\boldsymbol{E}_1}{\boldsymbol{\eta}_2}\right)\cdot\dot{\boldsymbol{\sigma}} + \frac{\boldsymbol{E}_1\cdot\boldsymbol{E}_2}{\boldsymbol{\eta}_1\cdot\boldsymbol{\eta}_2}\cdot\boldsymbol{\sigma} = \frac{\boldsymbol{E}_1\cdot\boldsymbol{E}_2}{\boldsymbol{\eta}_1}\cdot\dot{\boldsymbol{\varepsilon}} + \boldsymbol{E}_1\cdot\ddot{\boldsymbol{\varepsilon}} \tag{1}$$

Therefore, the solution for constant strain rate can be written as

$$\sigma(t) = \frac{E_1\cdot E_2}{\eta_1}\cdot\dot{\varepsilon}\cdot\frac{1}{a\cdot b\cdot(a-b)}\cdot\left[(a-b) + b\cdot e^{-a\cdot t} - a\cdot e^{-b\cdot t}\right] + \frac{\dot{\sigma}(0)}{b-a}\cdot\left(e^{-a\cdot t} - e^{-b\cdot t}\right) \tag{2}$$

with the constants “a” and “b”:

$$a = \frac{E_1+E_2}{2\cdot\eta_1} + \frac{E_1}{2\cdot\eta_2} + \sqrt{\left(\frac{E_1+E_2}{2\cdot\eta_1} + \frac{E_1}{2\cdot\eta_2}\right)^2 - \frac{E_1\cdot E_2}{\eta_1\cdot\eta_2}},$$
$$b = \frac{E_1+E_2}{2\cdot\eta_1} + \frac{E_1}{2\cdot\eta_2} - \sqrt{\left(\frac{E_1+E_2}{2\cdot\eta_1} + \frac{E_1}{2\cdot\eta_2}\right)^2 - \frac{E_1\cdot E_2}{\eta_1\cdot\eta_2}} \tag{3}$$

and

$$\dot{\sigma}(0) = E_1\cdot\dot{\varepsilon} \tag{4}$$

Comprehensive sensitivity studies on the influence of single parameters on the deformation representation of the model were conducted in Refs. [15,16]. Since most plastic materials react like non-Newtonian liquids, their dynamic viscosity is a function of shear rate. With the modification of the viscosity parameters η_1 and η_2, the yield stress will be increased or decreased respectively. The authors concluded from the sensitivity study, in which both viscosities show the same behaviour, that they can be described by identical functions. Apart from that, the variation of the stiffness serial spring (E_1) affects the initial stiffness of the stress-strain curve, while E_2 influences the stiffness in the non-linear region.

3. Materials

For experimental validation, the used polyurethane material was a two-component system (Rühl Puromer GmbH, Friedrichsdorf, Germany) where the polyol was puropreg® 569 IT based on polyetherpolyols and the isocyanate was puronate® 900 consisting of diphenylmethan-diisocyanat (MDI). The processing and mixing of the components was performed according to the manufacturer's formulation using a structural component spraying and mixing unit (KraussMaffei Technologies GmbH, Munich, Germany). Different foam densities were obtained (230 kg/m^3, 420 kg/m^3 and 610 kg/m^3) by spraying a defined mass of polyurethane mixture and allowing the foam to expand and to cure in the closed mould. After the processing, the foam was demoulded and left for 24 h at room-temperature for post-curing before preparing samples for mechanical testing. The specimens for compression test were cut out of the foam block using a parting-off grinder with cooling and lubricant liquids. Beyond that, the moulding skin (≈0.2 mm thickness) of the foam was cut off in order to prevent having the influence of non-uniform skin layers on the mechanical properties.

4. Parameter determination

In accordance with the proposed method by Ebert et al. in Refs. [15,16], quasi-static compression tests at reference strain rate in addition to dynamic mechanical analysis (DMA) for the determination of strain rate dependent parameter functions are determined for the prediction of strain rate dependent stress-strain relations for thermoplastic polymers. The objective of this work was to validate this method for cellular thermoset plastics based on rigid polyurethane foam. Material stiffness in the linear elastic region (E_1) and the visco-plastic region (E_2) are determined by compression tests at quasi-static reference strain rate for different foam densities. Since the bulk material consists of a thermoset polymer with brittle deformation behaviour, densification phenomena occur mainly in low density foam structures (Fig. 2).

For the dynamic mechanical analysis a DMA Q 800 (TA Instruments) in 3-point bending experiments over a frequency range from 0.01 Hz to 60 Hz for different maximum strains is used to determine the strain rate dependent parameter functions. The rectangular specimens were 3.4 mm thick, 60.0 mm long and 13.2 mm wide with a bearing distance of 50 mm, each anvil having

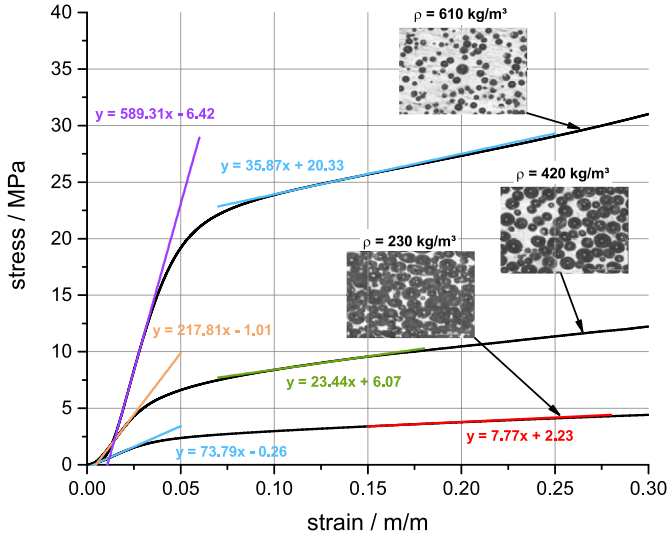

Fig. 2. Stress-strain curves of polyurethane foam with defined densities at reference strain rate of 0.002 s^{-1} and bilinear approximations.

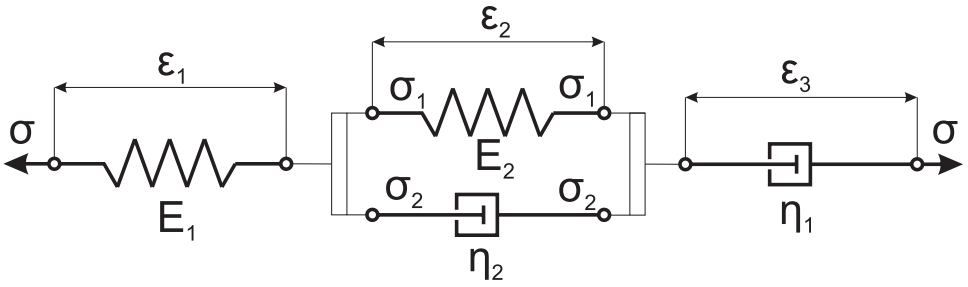

Fig. 1. Burgers model, a combination of linear-elastic (spring in series), viscoelastic (dashpot-spring combination) and visco-plastic (dashpot in series) material behaviour.

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