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Displacement rate and structural effects on Poisson ratio of a ductile structural adhesive in tension and compression

Myrsini Angelidi, Anastasios P. Vassilopoulos, Thomas Keller*

Composite Construction Laboratory (CCLab), Ecole Polytechnique Fédérale de Lausanne EPFL, Station 16, CH-1015 Lausanne, Switzerland

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ABSTRACT

The effects of the loading type, i.e. tension or compression, and displacement rate on the Poisson ratio of a non-linear viscoelastic ductile structural adhesive have been investigated using digital image correlation-based strain fields. The results showed that the Poisson ratio should be based on true strains to take geometry changes into account. In tension, the ratio exhibited a slight dependency on the true strain level below the yield point and on the displacement rate. The rate dependency was confirmed in regions with necking, where the Poisson ratio locally decreased. Subjected to compression, the ratio was affected by out-of-plane deformations of the specimens and thus exhibited values above 0.5. The necking in tension and out-of-plane deformations in compression may be considered as structural effects on the Poisson ratio that may be attributed to changes in the molecular structure of the polymer.

1. Introduction

In civil engineering, new structural materials with promising new physical and mechanical properties are appearing in bridge and building construction, such as fiber-reinforced polymers or structural glass. A common feature of these materials is that they behave in a more or less brittle manner, similar to the generally used timber. In order to overcome this drawback, i.e. compensate for the lacking material ductility, ductility can be incorporated on the structural system level, e.g. by using ductile structural joints [1]. An appropriate type of such joints can be developed using ductile structural adhesives, as has already been proved experimentally [2,3]. Since the stress state in such adhesive joints is complex, the adhesive is subjected to different types of loading and loading rates, which may vary significantly, even locally, and to which the adhesive response may be very sensitive due to its viscoelastic nature [4]. Furthermore in the numerical modeling of such joints the Poisson ratio is required as an input parameter and the question arises as to what extent this ratio is a constant or depends on loading type and rate.

Originally, the Poisson ratio was defined as a constant value for elastic, isotropic materials, linking the transverse to the longitudinal deformations upon uniaxial loading [5]. The ratio may vary between −1 and 0.5 for linear, isotropic materials and within this range macroscopically homogeneous materials normally exhibit values between 0.2 and 0.5 [6]. However, experimental evidence has also shown values below and above this first interval, mainly due to structural effects in foam-like or porous materials [7–9] or anisotropic composites [10–13]. Most of the investigations concerning the Poisson ratio have been based on tensile loading and thus values based on compressive loading are rare, e.g. [14,15].

In the case of viscoelastic materials, such as adhesives and elastomers, that exhibit time- and temperature-dependent material properties, the Poisson ratio is no longer constant but varies with time and temperature [16–18]. Mechanisms that soften the polymer, such as viscoelastic flow (i.e. creep or relaxation [18–20]) or increasing temperature [21], increase the Poisson ratio which then tends towards the 0.5 limit of an incompressible fluid [22]. The ratio is thus particularly loading rate-dependent and increases with decreasing loading rate [23]. Furthermore, in necking regions exhibiting higher strain rates, a corresponding decrease of the Poisson ratio has been observed [23].

In this work, a ductile acrylic structural adhesive used to develop ductile joints in timber structures is investigated. The viscoelastic material is subjected to different loading types (tension and compression) and different displacement rates in the joint. In order to mechanically characterize the adhesive, the quasi-static tensile and compressive behavior under different displacement rates was experimentally investigated, also taking large non-linear strain development into account. It was of primary interest to understand the effect of the loading type, the displacement rate and the associated highly non-linear response on the Poisson ratio, which is required for subsequent numerical modeling of the joint behavior.

* Corresponding author.

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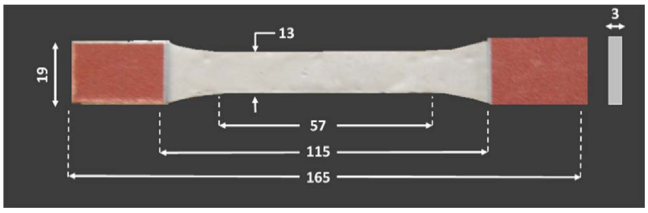

Fig. 1. Tensile specimen (ASTM D638).

2. Experimental Set-up and instrumentation

2.1. Material and specimen fabrication

The investigated material is a two-component, fast-curing commercial acrylic adhesive (SikaFast5221NT), which is based on ADP (Acrylic Double Performance) technology and provided by Sika Schweiz AG. The two components (SikaFast5221NT and SikaFast5200) are mixed at a ratio of 10:1 (by volume), using a suitable mixing gun for the adhesive application. The adhesive is highly deformable and exhibits a ductile behavior [2].

The specimens for tension loading were fabricated according to ASTM D638 [24] using aluminum molds. A dog-bone shape of 165-mm length by 13-mm width and thickness of 3 mm was selected and aluminum tabs covered with sand paper were glued to the specimen ends to prevent grip failure and slippage, see Fig. 1. The specimens for compression loading were based on ASTM D695-96 [25], with a square cross section of 12.7 mm and a height of 25.4 mm, see Fig. 2. A plate of 12.7-mm thickness was produced and the compressive specimens were cut using a water-jet cutting machine. Furthermore, three rectangular-shaped specimens with dimensions $35 \times 10 \times 3$ mm^3 were fabricated for Dynamic Mechanical Analysis (DMA) investigations in a single-cantilever beam configuration according to ASTM E1640 [26]. After fabrication, all specimens were cured for 24 h under ambient laboratory conditions (21 ± 3 °C and 38 ± 10% relative humidity) and then post-cured at 50 °C for seven days to obtain fully cured specimens.

2.2. Experimental program and instrumentation

Three DMA experiments were performed using a TA Instruments Q800 thermodynamic mechanical analyzer (DMA) to obtain the glass transition temperature, T_g, storage modulus, E', and loss modulus, E''. All experiments were run from −100 °C to +100 °C, at a rate of 1 °C/min, an amplitude of 15μm and a frequency of 1 Hz.

An MTS 810 Landmark testing frame with a 2.5-kN load cell was used for the tensile experiments and a W+B 250-kN capacity testing machine for application of the compressive loading by using two parallel plain steel plates, covered with Teflon sheets to reduce friction. All experiments were conducted under ambient laboratory conditions using displacement-control mode. The tensile specimens were loaded up to failure. Since no failure occurred in compression, all experiments were stopped at a displacement of d = 20 mm, corresponding to 80% of the initial specimen height.

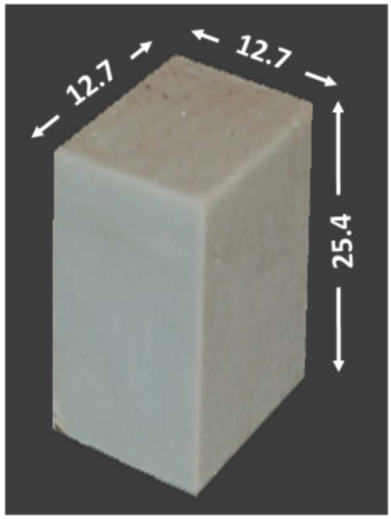

Fig. 2. Compressive specimen (ASTM D695-96).

Five different displacement rates were selected for each type of experiment, ranging around the rates recommended by the standards (5 mm/min ± 0.25% for tension [24] and 1.3 mm/min ± 0.25% for compression [25]), so that failure would occur within 0.5 to 5 min. In tension 2, 10, 50, 100 and 200 mm/min were applied and in compression 0.2, 2, 5, 10, and 20 mm/min. Three specimens were investigated at each displacement rate; they were labeled according to the material (A for Acrylics), type of loading (T or C for tension or compression), rate of displacement applied (e.g. 10 for 10 mm/min) and designation of the specimen (a, b or c). The complete experimental matrix, which includes 15 tensile and 15 compressive specimens, is shown in Tables 1 and 2. Also indicated are the engineering strain rates which correspond to the displacement rates.

The load and specimen displacements were obtained from the machine readings. Furthermore, the full 3D strain field was measured on one surface of each specimen using a Digital Image Correlation (DIC) System. As schematically shown in Fig. 3, this system includes two digital cameras focused symmetrically on the measurement area at ± 30°. Detailed information about the DIC system is given in Refs. [27,28]. A random pattern of black speckles of similar size was sprayed on all specimens, allowing the DIC to track their relative displacement during the experiment. Different image recording frequencies, between 0.01 Hz and 5 Hz, were selected according to the applied displacement rates. The displacement at a specific point was calculated based on the average displacement of the speckles in a square area (centered on the selected point), which is defined by the filter and step size and approximately corresponds to 12 mm × 12 mm for tension and 3.5 mm × 3.5 mm for compression. Each deformed image was correlated with the initial un-deformed image and the resulting displacement fields were smoothed and processed to obtain strain data. The accuracy of the measurements, based on the 68% confidence intervals at the failure load level [28], is ± 0.01 mm for displacements and ± 0.001 for strains and for the strain-based Poisson ratio.

3. Experimental Results

3.1. DMA experiments

The DMA curves shown in Fig. 4 indicate that the onset of the glass transition temperature is $T_{g,onset}$ = 43 °C, if the storage modulus is considered (defined as the point of interception of the two tangents) or $T_{g,tan\delta}$ = 68 °C according to the peak of the tanδ curve. Although the transition zone was broad, the adhesive was considered to be in the glassy state at laboratory temperature (21 ± 3 °C).

3.2. Tension experiments

Typical tensile load vs displacement responses for each displacement rate, obtained from the machine measurements, are shown in Fig. 5. Also indicated are the corresponding engineering stresses and strains. The material exhibited a non-linear behavior, with an initial stiffer response up to a local maximum, referred to as yield load. For different loading rates, different yield loads and post-yield behaviors could be observed. The yield load significantly increased with higher displacement rates; however, the corresponding displacement was almost rate-independent, i.e. at around 10 mm. Above the yield point, the stiffness decreased at higher rates until failure occurred. At lower rates, however, the stiffness started increasing again up to a second higher