Construction and Building Materials 140 (2017) 184–193

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Ductility, recovery and strain rate dependency of an acrylic structural adhesive

Myrsini Angelidi, Anastasios P. Vassilopoulos, Thomas Keller *

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

HIGHLIGHTS

- Different properties resulted for tension and compression at similar strain rates.
- Increasing the strain rate increased most properties with a logarithmic trend.
- The acrylic adhesive exhibited high energy-based ductility indices.
- The time-dependent recovery after unloading was modeled by a Weibull-based model.
- High recovery after 48 h implied that no residual deformation was caused by damage.

ARTICLE INFO

Article history:
Received 21 December 2016
Received in revised form 19 January 2017
Accepted 19 February 2017
Available online 1 March 2017

Keywords:
Adhesives
Acrylics
Ductility
Recovery
Strain rate
Viscoelasticity

ABSTRACT

The ductility and time-dependent recovery of a ductile acrylic adhesive were investigated in this work. The quasi-static true tensile and compressive strain behaviors were examined at different strain rates, taking large deformations into account. Yield stress, elastic modulus, and failure strain exhibited a logarithmic dependency on increasing strain rate, while yield strain and stiffness after yielding were insensitive to strain rate. High energy-based ductility indices were obtained compared to traditional materials. The time-dependent recovery after unloading depended on loading type (tension or compression), the strain rate of loading, and the strain at unloading. The delayed recovered strain development was modeled using an existing Weibull-based model for creep recovery. The strain after unloading almost fully recovered after 48 h, indicating that no residual deformation caused by damage or plastic flow occurred.

1. Introduction

In building and bridge construction, the field to which this work applies, an essential requirement for structural systems is ductility, which is the ability of a material or structural system to sustain inelastic deformation prior to collapse, without loss of resistance. Such a behavior increases the robustness and structural safety through load distribution in the case of overloading or local failure if the system is redundant.

The easiest way to provide ductility is through the use of ductile materials such as steel or reinforced concrete. If the materials are brittle however, as is the case with fiber-reinforced polymer (FRP) composites and very often also timber, providing ductility is much more difficult. One approach is to develop ductile joints from brittle components, i.e. by using ductile connectors made of steel for example, or by applying ductile structural adhesives. The feasibility of the latter has already been experimentally proven in [1], where a ductile acrylic adhesive was used to join two FRP beams to a continuous two-span beam which then exhibited load redistribution similar to that occurring in an equivalent steel beam.

In elastoplastic materials such as steel, ductility is characterized by a permanent residual deformation after unloading, while in viscoelastic materials, such as structural adhesives, this remaining deformation after unloading partially or completely recovers. A systematic investigation of the potential level of ductility and the recovery behavior of adhesives has not yet been performed. Furthermore, adhesives have a response that is highly dependent on loading rate, which also differs according to whether they are subjected to tensile or compression loading [2–4].

On the material level, ductility is normally defined as the ratio between the ultimate and yield deformation [5]. On the structural system level, however, this definition is not always accurate and applicable since mechanisms with effects similar to material

* Corresponding author.
E-mail address: thomas.keller@epfl.ch (T. Keller).

http://dx.doi.org/10.1016/j.conbuildmat.2017.02.101
0950-0618/

ductility, designated pseudo-ductility, can also be achieved in systems composed of only brittle materials or components, if the system is redundant [1,5]. Instead of expressing ductility in terms of deformations, a characterization based on dissipated energy is more appropriate in such cases, i.e. by comparing the dissipated inelastic energy, E_{inel}, and elastic energy, E_{el}, whereby their sum is the total dissipated energy, $E_{tot} = E_{inel} + E_{el}$.

In a stress-strain curve, the inelastic energy corresponds to the area between the loading and unloading curves, while the elastic energy is characterized by the area below the unloading curve, as shown in Fig. 1. In the case of viscoelastic materials, where the onset of the reloading path depends on the recovery after unloading, the inelastic energy is further split into the hysteretic energy, i.e. the area between the unloading and reloading paths and the energy attributed to plasticity or damage, i.e. the area between the loading and reloading path, the latter after full recovery [5,6]. Based on these energy definitions, different ductility indices are proposed in literature, which all comprise different ratios of these energies, e.g. E_{inel}/E_{tot} [7,8] or E_{tot}/E_{el} [9].

Recovery after unloading is a time-dependent process during which the deformed viscoelastic molecular network attempts to recover its initial structure, as shown in Figs. 1 and 2. In terms of strain, the total recovered strain, $\varepsilon_{r,tot}$, is the sum of the instantaneous recovered strain during unloading, $\varepsilon_{r,0}$, (path A-B), the delayed recovered strain, $\varepsilon_{r,del}(t)$ (path B-C, attaining its maximum level after infinite time, $\varepsilon_{r,del}^{\infty}$), and the residual strain, $\varepsilon_{r,res}$, if some unrecoverable plastic flow or damage occurred [5].

Concerning the modeling of viscoelastic recovery behavior, an exponentially stretched function was developed by Williams and Watts [10] to represent time-dependent phenomena (mainly relaxation) in amorphous materials, based on the decay function of Kohlrausch [11]. The function has a form similar to that proposed earlier by Weibull [12] for dielectric decay; the latter was then also applied to describe time-dependent creep [13–15]. Further works focused on the creep-recovery description [16–18], while [16] was also applied to the model time-dependent recovery of viscoelastic deformations, after unloading, in the web-flange junctions of pultruded FRP bridge decks [5].

This work aims to contribute to a better understanding of the ductile and recovery behaviors of flexible polymers such as acrylic adhesives. Standardized specimens of a commercial acrylic adhesive were subjected to either axial tension or compression loading at different strain rates in order to evaluate the effect of the latter on the true stress-strain behavior, i.e. by also taking large deformations into account. Furthermore, tensile and compressive specimens were subjected to an unloading and reloading cycle, the latter after different periods of recovery. The ductility and recovery behaviors in tension and compression were thus characterized and compared.

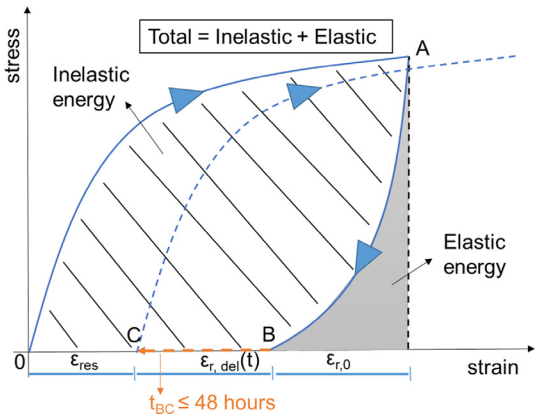

Fig. 1. Dissipated inelastic and elastic energy and time-dependent recovery (schematic representation).

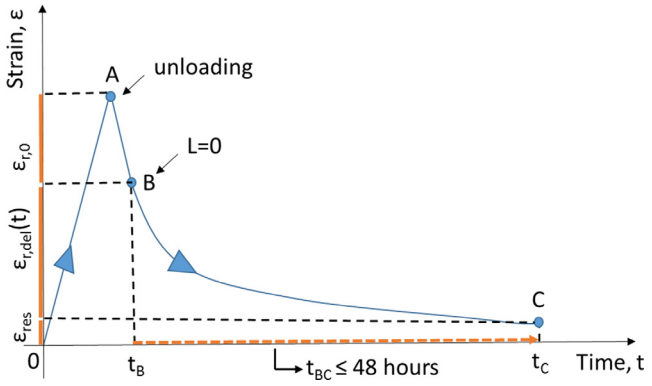

Fig. 2. Strain recovery after unloading (schematic representation).

2. Experimental set-up

2.1. Material and specimen fabrication

A commercial structural acrylic adhesive was used in this study. The two-component adhesive (SikaFast 5221NT, from Sika AG) is based on the ADP (Acrylic Double Performance) technology and is fast-curing [19]. The specimens for tension were fabricated according to ASTM D638 [20] in a dog-bone shape and the grip area was reinforced with aluminum tabs. The specimens for compression were manufactured according to ASTM D695-96 [21]; the orthogonal parallelepipeds had a squared cross section of 12.7 × 12.7 mm and a height of 25.4 mm.

The specimens were fabricated according to the supplier's specifications, using a suitable mixing gun for application. While aluminum molds were used for the tensile specimens, the compressive specimens were cut using a water jet from plates of 12.7-mm thickness, taking special care to obtain parallel edges for the uniform distribution of the compressive load. The specimen dimensions (total length, width and thickness) were measured using a caliper with an accuracy of 0.01 mm. They were fabricated and cured for 24 h under ambient laboratory conditions (21 ± 3 °C and 38 ± 10% relative humidity) and then post-cured at 50 °C for at least four days, after being removed from the molds or cut from the plates, in order to obtain fully cured specimens.

It should be noted that preliminary investigations using dynamic mechanical analysis (DMA), reported in [4], already showed a significant sensitivity of the storage modulus to small temperature variations under laboratory conditions; the onset of the glass transition temperature range occurred at 43 °C based on the storage modulus. For this reason, great emphasis was placed on assuring full curing of the specimens and the curing degree was thus validated by preliminary differential scanning calorimetry (DSC) investigations during curing and after post-curing.

2.2. Experimental procedure and instrumentation

An MTS 810 Landmark machine equipped with a load cell of 2.5-kN capacity and a W+B 250-kN capacity machine were used for the tensile and compression experiments respectively. All experiments were conducted under ambient laboratory conditions, under displacement-control mode. The ASTM standards for this type of polymer suggest an average rate of 5 mm/min ± 0.25% for tension [20] and 1.3 mm/min ± 0.25% for compression [21]. In