International Journal of Adhesion & Adhesives 52 (2014) 26–30

Contents lists available at ScienceDirect

International Journal of Adhesion & Adhesives

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

Generalized analytical solution for compressive forces in adhesively-bonded-joint assembling

L. Bergamasco, S. Izquierdo*, E. Duvivier, J.M. Royo, A. Chiminelli, M.A. Jiménez

Instituto Tecnológico de Aragón (ITA), María de Luna 8, 50018 Zaragoza, Spain

ARTICLE INFO

Article history:
Accepted 19 March 2014
Available online 30 March 2014

Keywords:
Squeeze-flow forces
Adhesively-bonded joints
Herschel–Bulkley model
Analytical
Numerical
Experimental

ABSTRACT

Normal forces exerted by the adhesive to the substrate during the squeeze flow occurring in compaction of bonded joints are analyzed using theoretical, numerical and experimental techniques. An analytical solution, derived from the squeeze-flow theory of a viscoplastic material, is generalized to be valid for any initial shape of the adhesive cord. The rheology of the material is modeled according to the Herschel–Bulkley model and is fitted with experimental data available from the characterization of an epoxy-based adhesive. The analytical law is compared with a numerical model, where the two-phase problem for the squeeze-flow test is solved by finite-volume methods using a commercial CFD solver. The results obtained with these two approaches show excellent agreement with experimental forces obtained for a wedge-shaped specimen. The proposed methodology can therefore be useful for the optimization of the bond lines in assembling processes.

1. Introduction

During the last years, the utilization of adhesive-bonding techniques has seen a remarkable growth. Besides their lower production cost indeed, these procedures offer several important advantages over conventional mechanical fasteners, such as high strength-to-weight ratio, resistance to corrosion and degradation in aggressive environments, continuity and impermeability of the joints, efficient bonding of dissimilar or heterogeneous materials and, through a careful selection of the materials, and a high capacity for energy and vibration absorption [1].

However, in large assemblies the thickness and shape of the adhesive cord can strongly affect the strength of the joints and thus of the component [2]. This is a well known issue, especially for rigid or toughened structural adhesives, where significant reductions of the maximum load capacity of the joints are observed if the bondline thickness deviates from an optimum value. This phenomenon is sometimes associated to a change in the failure mode (from cohesive to adhesive, generally for thicknesses lower than the optimum one) and in other cases it is produced by a raise in the stress concentration that usually appears in the extremes of the overlaps (when the thickness exceed the optimum one). For a comprehensive overview of these issues the reader is referred to [3,4] and references therein. For these reasons the compaction process constitutes a critical phase that must be adequately controlled to guarantee the final quality of the joints. In particular, the assembly process must be designed to ensure a final thickness within the admissible ranges, in order to guarantee the required mechanical performance. In certain cases, the adhesive thickness along the bonded areas cannot be controlled through gauges or spacers, thus the final result mainly depends on the forces imposed during compaction.

In this work we analyze these forces by means of analytical tools, a two-phase numerical model and experimental measurements. The test case is the squeeze-flow of an epoxy-based adhesive, whose rheology is modeled according to a viscoplastic constitutive law (Herschel–Bulkley model), fitted with experimental data available from a characterization. An analytical solution is generalized to be valid for any initial shape of the adhesive cord (wedge-shaped in this work). The numerical model is intended as an auxiliary tool, whose utilization in conjunction with the analytical law allows to correctly predict compressive forces in complex adhesive shapes. The aim of this crossed analysis is to provide valuable information about the limits of each technique and about how to combine them to accurately predict compaction forces for different geometries. Finally, the control of the compaction forces allows optimizing the parameter set-up in the assembly process.

The outline of the paper is as follows: the experimental set-up is firstly briefly explained; successively the analytical and numerical approaches are discussed. The results obtained and the

* Corresponding author. Tel.: +34 976 011 199; fax: +34 976 011 888.
E-mail address: sizquierdo@ita.es (S. Izquierdo).

http://dx.doi.org/10.1016/j.ijadhadh.2014.03.010
0143-7496/

comparison between the approaches with experimental data are presented in Section 3. A brief discussion of the results and of the proposed methodologies concludes the paper.

2. Methodology

2.1. Experimental set-up

The squeeze tests were performed using the experimental set-up shown in Fig. 1. A squeeze tool, internally designed, was mounted in a MTS Universal Testing Machine (model Alliance RF100) [5]. The tests were conducted with two load cells: a 1 kN load cell for the tests on the cylindrical specimens and a 100 kN one for those on the wedge-shaped specimens. The tests were performed with a cross-beam velocity between 50 mm/min and 250 mm/min. The squeeze tool is based on guided parallel plates. The four vertical columns ensure a uniform distribution of pressure over the specimen. The lower aluminum plate is fixed to the frame plane, whilst the upper one is assembled to the mobile crossbeam of the universal machine. For the squeeze, a wooden block covered by kraftliner paper was mounted on the upper plate using bolts. In order to contain the lateral overflow of the material, for the wedge-shaped specimen additional aluminum profiles were added to the lower plate. The gap between these profiles and the wooden block was adjusted to guarantee a friction-free vertical movement. The adhesive samples were previously prepared on separate plates. The shape of the specimens (cylindrical or wedge-shaped) was obtained by firstly using a palette for a preliminary modeling and then accurately finished with a laser-cut steel. Each specimen was tested on its individual plane used for the preparation, which was correctly positioned and fixed to the universal machine. Force values were instantaneously recorded by TestWorks® 4 [6].

2.2. Analytical model

Analytical solutions for squeeze-flow are typically derived for cylindrical samples [7] as shown in Fig. 2(a). For this case, the following conditions are considered: a constant velocity $V = -dH/dt$; an inter-plate volume $\pi R^2_{\max} H$, which is assumed to be always full of material and thus the contribution to the force of the overflow (when squeezing beyond R_{max}) is neglected; a rheology given according to the Herschel–Bulkley model, which in scalar form reads

$$\tau = \tau_0 + K\dot{\gamma}^n; \tag{1}$$

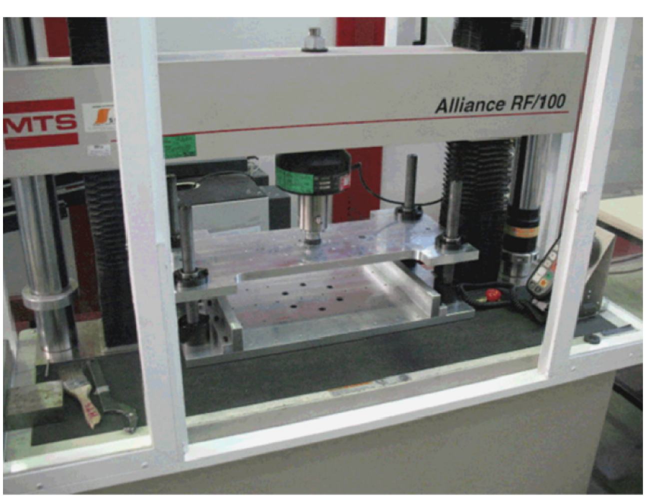

Fig. 1. Experimental system used for the characterization and the squeeze-flow tests.

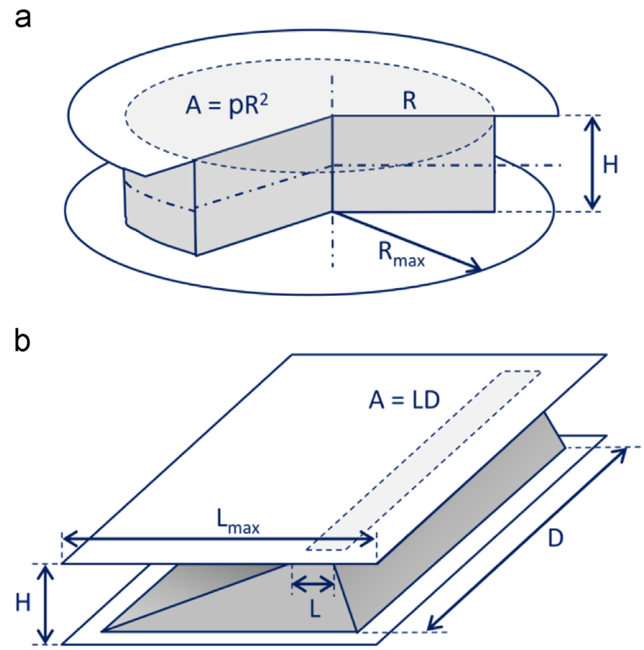

Fig. 2. Schemes for the analytical solution: cylindrical (a) and wedge-shaped (b) geometries. The dimensions are as follows: H ranges from 10 to 25 mm; L_{max} is 160 mm, R ranges from 15 to 30 mm and D ranges from 100 to 400 mm.

where τ_0 is the yield shear–stress threshold, K the consistency index and n the power-law index. This configuration has been previously studied [8,9], particularly, Adams et al. [10] demonstrated that for no-slip boundary conditions at the walls and a plasticity number defined as $S = (RVK^{1/n})/(H^2 \tau_0{}^{1/n})$, in the ranges $0 < S < 100$ and $0.1 < n < 1$ the mean pressure has the following form:

$$\overline{p} = \frac{F}{\pi R^2} = \sigma_0 + \frac{R\tau_0}{H}\left[\frac{2}{3} + \frac{2}{n+3}\left(\frac{2n+1}{n}\right)^n S^n\right]; \tag{2}$$

where σ_0 is the uniaxial yield stress. It is typically assumed that $R/H \gg 1$ and that the contribution of σ_0 is negligible as compared with $R\tau_0/H$. However, these two simplifications must be avoided for generalizing the solution to arbitrary shapes of the sample, see for example Fig. 2(b). For the generalization, the contact area must be a function of the contact length L. Thus, for cylindrical samples $L = R$ and the contact area is computed as $A = \pi L^2$. For wedge-shaped samples this contact area is $A = LD$. The definition of the generalized plasticity number S is then

$$S = \frac{LV}{H^2}\left(\frac{K}{\tau_0}\right)^{1/n}; \tag{3}$$

and the generalized expression for the compressive force follows from Eq. (2)

$$F = \sigma_0 A + \frac{2LA}{3H}\tau_0 + \frac{2LAK}{(n+3)H}\left(\frac{2n+1}{n}\right)^n \left(\frac{LV}{H^2}\right)^n + O\left(\frac{H}{L}\right)^2. \tag{4}$$

The yield stress threshold is straightforwardly defined from the above equation in the limit of $V \to 0$ and neglecting σ_0 as

$$\tau_0 = \frac{3HF}{2LA}. \tag{5}$$

When working at constant force, an expression for the velocity as a function of the force can be obtained from Eq. (4) and can be used to compute the separation height as a function of time as $H(t_n) = H(t_{n-1}) - V\delta t$, where the explicit expression for the squeeze