

# A COHESIVE ELEMENTS BASED MODEL TO DESCRIBE FRACTURE AND COHESIVE HEALING IN ELASTOMERS

A. Baldi <sup>1</sup>, A. M. Grande <sup>1</sup>, R. K. Bose <sup>2</sup>, A. Airoidi <sup>1</sup>, S. J. Garcia <sup>2</sup>,  
L. Di Landro <sup>1</sup>, S. van der Zwaag <sup>2</sup>

<sup>1</sup> *Dipartimento di Scienze e Tecnologie Aerospaziali, Politecnico di Milano, via La Masa 34, 20156, Milano, Italy - e-mail: baldi@aero.polimi.it; grande@aero.polimi.it; alessandro.airoidi@polimi.it; luca.dilandro@polimi.it*

<sup>2</sup> *Novel Aerospace Materials, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands - e-mail: r.k.bose@tudelft.nl; s.j.garciaespallargas@tudelft.nl; s.vanderzwaag@tudelft.nl*

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## ABSTRACT

Several polymeric systems with intrinsic Self-Healing (SH) capabilities have been reported in literature. Many of them showed healing upon contact across the crack interface. Different parameters such as contact time, temperature, pressure or chemical activity determine the degree of healing obtained.

In this work, a numerical simulation of the healing efficiency as a function of the environment is proposed based on the use of cohesive elements in a finite element model. Cohesive elements are commonly used to model interlaminar fracture mechanisms in composite materials. In this work, they are adopted to simulate both failure and subsequent healing by a specific SH elastomeric system.

The SH elastomeric system is initially characterised by means of the identification of its conventional mechanical properties. From these results, a hyperelastic constitutive model is selected. At the same time, a model simulating fracture mechanics and healing mechanics is established and validated using a cohesive failure model in a commercial explicit finite element code. Finally, the two models are combined to evaluate the capability of the proposed numerical approach to simulate: (i) the restoration of contact of the two separated sides of the material during their re-joining, and (ii) the restoration of the mechanical properties of the elastomeric system. This later stage is directly linked to the healing efficiency. While the model does not yet capture all features of healing, it offers attractive features worth further exploring also for other SH systems.

## 1. INTRODUCTION

Damage propagation in elastomeric materials plays a fundamental role in many applications (e.g. seals, vibration absorbers, tyres) and the implementation of SH concepts to rubbers can extend the lifetime of structures manufactured with this innovative approach [1-3].

In this context, experimental and numerical results for the crack propagation and subsequent healing of a commercial supramolecular SH rubber are presented.

## 2. MATERIALS

The SH rubber Reverlink<sup>®</sup> grade HR, provided by Arkema in the non-cured version, was used. The supplied elastomer is characterized by a density and a glass transition temperature of 1.09 g/cm<sup>3</sup> and 10±5 °C, respectively (producer datasheet). Uncured polymer was cast into a rectangular PTFE mould and subsequently cured in oven at 120 °C for 24 hours producing samples of typical dimensions 100x40x1 mm.

## 3. METHODS

Tensile and relaxation tests were performed using rectangular samples at different strain rates and strain levels, respectively. Obtained results were employed to calibrate a visco-hyperelastic model for the following numerical simulation.

Regarding damage, the energy necessary to extend a fracture plane is a material property that can be measured using different approaches (Figure 1), each providing a simple way to evaluate the failure behaviour of rubbery materials [4,5]. In this work, both tensile and tear samples were employed.

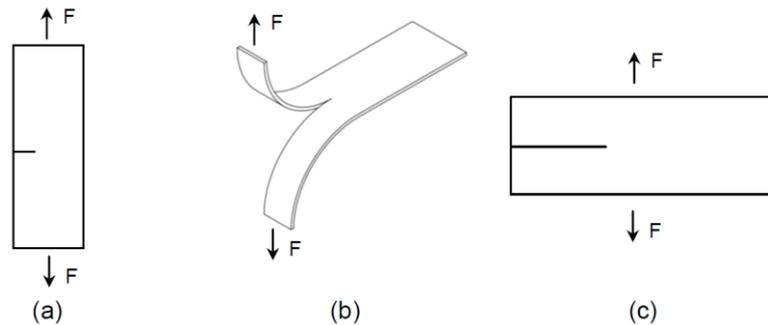


Figure 1: Tensile (A), Trouser tear (B) and pure shear test specimens (C).

The fracture propagation process experienced by the specimen in the tensile test schematically reported in Figure 1-(A) has been simulated by adopting a cohesive zone modelling approach in an explicit FE code. In order to overcome the typical problems related to the introduction in the FE scheme of high initial penalty stiffness values  $K_n$  for the conventional cohesive elements, which are characterised by infinitesimal or zero thickness, the cohesive zone model has been implemented in finite thickness solid elements with reduced integration scheme [6].

The specimen was modelled using solid elements with reduced integration scheme endowed with a visco-hyperelastic material model. In particular, a Marlow hyperelastic material model has been calibrated and integrated with a three-element Prony series.

Cohesive fracture processes along the crack propagation path has been described by means of the relative displacement ( $\Delta = \mathbf{S}^+ - \mathbf{S}^-$ ) between the mid-point of the surface of the adjacent solid elements, which are sketched in Figure 2-(A). The components of the relative displacement vector,  $\Delta$ , can be associated to the three possible modes of fracture opening, as indicated in Equation (1).

$$\Delta_I = \begin{cases} \Delta_z & \text{if } \Delta_z > 0 \\ 0 & \text{if } \Delta_z \leq 0 \end{cases} ; \Delta_{II} = \Delta_x ; \Delta_{III} = \Delta_y \quad (1)$$

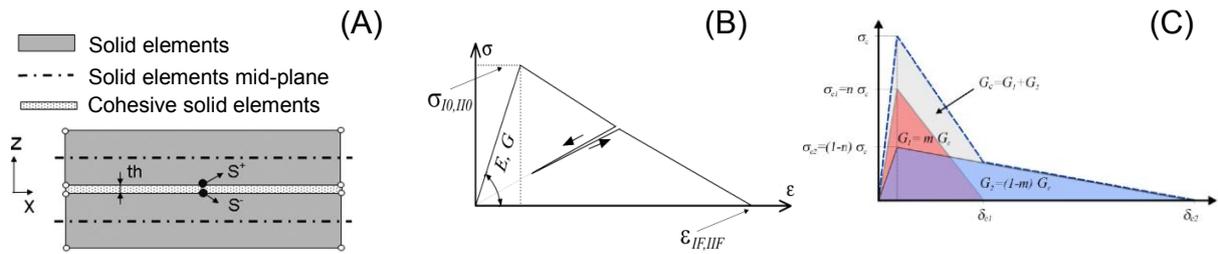


Figure 2: Scheme of the modelling technique (A), bi-linear response (B) and two superimposed bi-linear responses (C) adopted in the cohesive elements.

A scalar damage variable  $d$  is introduced in the cohesive elements to obtain the bi-linear response that has been reported in Figure 2-(B). The onset and evolution of such a damage variable can be tuned to model the strength and the toughness of the material at the location of the crack. To accomplish such an objective, the links between the critical energy release rates and the energy dissipated in the damage process are exploited [6]. For mode I opening, the link is expressed by Equation (2).

$$\int_0^{\infty} \sigma_{zz} d\Delta_I = t_k \int_0^{\infty} \sigma_{zz} d\varepsilon_{zz} = G_{Ic} \quad (2)$$

A separate material model can be used in the simulation of the healing process by simply introducing a relation between the duration of the process, the applied pressure and the mechanical properties recovered through the healing mechanism. The recovery of the mechanical properties can be obtained by reducing the value of damage parameter.

The simplest law that can model both strength and toughness in the cohesive layer is the bi-linear one shown in Figure 2-(B). Nevertheless, the shape of the response after the maximum stress may have a noticeable impact in the case of a non-negligible length of the process zone at the crack tip. This happens in the case of bridging phenomena and requires a special shape of the cohesive response. The requirement response can be obtained by using two superimposed cohesive elements, as shown in Figure 2-(C) [7].

#### 4. RESULTS

In the model of the tensile test shown in Figure 3-(A), the strength of the cohesive layer was taken by considering the maximum stress obtained in a tensile test on an unnotched specimen. In the first round of analyses, the viscoelastic behaviour of the elastomer was neglected and a bi-linear cohesive law was used. The toughness attributed to the cohesive element had been derived from a standard tear test (Figure 1-(A)). Numerical results showed that an unstable propagation process was obtained, whereas a progressive crack propagation was apparent in the experiments. The quantitative and qualitative discrepancies between numerical and experimental responses remained unacceptable even if toughness was significantly increased (Figure 3-(B)). Correlation was improved with the introduction of viscoelastic behaviour and of a tri-linear cohesive response defined by adopting two superimposed cohesive elements. In the response presented in Figure 3-(B), the maximum loads are captured by the numerical model. The progressive crack

propagation is represented and the displacement at failure tends to be close to the experimental results. The peculiar shape in the crack region during the failure of the specimen is qualitatively modelled, as can be seen by comparing Figure 3-(A) and Figure 3-(C).

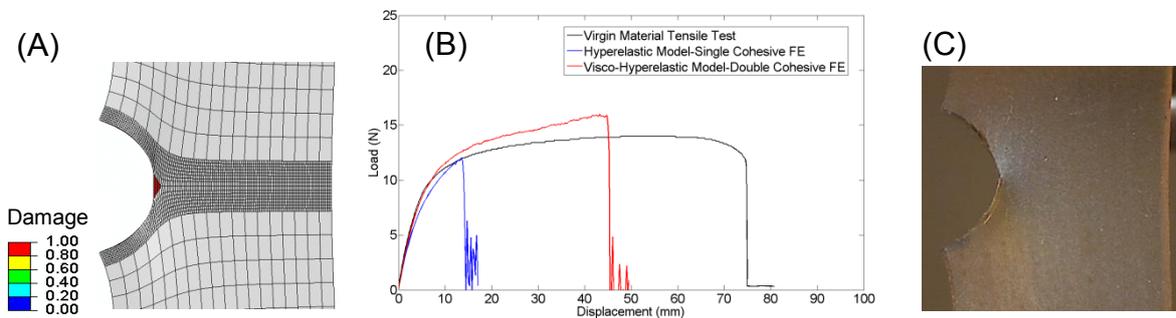


Figure 3: FE Model of the tensile test (A), numerical vs. experimental response correlation (B) experimental evidence (C)

## 5. CONCLUSIONS

The obtained results show that the fracture process in a healed supramolecular rubber can be modelled using a cohesive zone approach implemented in an explicit finite element code. The importance of properly representing the visco-hyperelastic behaviour and the strain softening response in the cohesive law has been outlined. Such aspects complicate the identification of material parameters, which could be obtained by means of optimization procedures. The numerical approach could represent a valuable tool for the identification of the healing effect in elastomers, overcoming the limitation of data reduction techniques applied to standard tests. Moreover, the material model could be used for simulation of healing process under externally applied load and to predict the mechanical properties of healed elastomeric layers in real-world applications.

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