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# Simplified modelling of bonded assemblies for the mechanical characterisation of adhesives and the analysis of their water ageing

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**Abstract**. The ageing of adhesives is of major interest to the marine industry because the mechanical properties of these materials change with long-term exposure to moisture. The aim of this paper is to model the mechanical behaviour of such adhesives in bonded assemblies, taking into account the effects of water ageing. Based on experimental tests, the behaviour of a chosen adhesive is calibrated for different levels of water absorption. An elastoplastic behaviour law of the Mahnken-Schlimmer type is used to describe the non-linear behaviour of the adhesive. The material parameters depend on the water content. In this study, an enriched 1D finite element model is developed, allowing an accurate description of all the deformation and stress states, particularly within the adhesive joint. Numerical simulations using 2D finite elements are also carried out for validation purposes.
**Keywords:** bonded assemblies, water ageing, mechanical characterisation, finite element simulation.

## INTRODUCTION

The increasing use of structural bonding as an assembly method is becoming more and more widespread in various sectors of industry, including the marine field. The main advantages of this technique are reducing the weight of ships and facilitating the assembly of the various materials involved, particularly when composites or hybrid (metal/composite) structures are involved. As a result, studying the mechanical behaviour of adhesives and bonded assemblies is of real interest to the naval industry. In harsh environments (such as in the presence of seawater), the use of epoxy adhesives is predominant. As their mechanical and physical properties evolve over time due to hydric aging, it is crucial to establish a reliable and effective characterization of the behavior of these adhesives throughout the lifetime of assemblies.

In this paper, a Mahnken-Schlimmer type model was chosen to describe the mechanical behavior of adhesives, as this type of model has been commonly used and experimentally validated in this context [1,2]. It is an elastoplastic (non-associated) model suitable due to its ability to describe the complex (non-linear) behavior of adhesives (including the influence of hydrostatic pressure [3]). Moreover, while numerical modeling of the mechanical behavior of bonded assemblies is generally performed using 2D or 3D finite element models (with necessarily refined meshes and therefore extremely costly in terms of computation time), recent works [4] have highlighted the potential of a simplified model (based on enriched kinematics), capable of describing the deformation and stress fields within the assembly (joint and substrates) in a reduced dimension (1D), thus allowing for lower computation times without sacrificing precision. The adaptation of this simplified model to the context of hydric aging therefore proves to be a very interesting alternative for an effective prediction of the mechanical behavior of bonded joints over time.

Furthermore, the requirement for repeated calibration of this behavior law led to the definition of a simplified calibration strategy in terms of experimental approach, adapted from the work of Ilioni [5,6], achieving a good compromise between accuracy of results and implementation time. This strategy is based on identification tests for different load cases (tensile and shear) carried out on aged epoxy adhesive mass samples. The parameters of the behavioral model were then identified using numerical modeling of the tests, in a reverse procedure.
In this work, experimental calibration tests (tensile/shear) were first carried out on bulk adhesive samples aged at different humidity levels (from dry state to immersion). The parameters of the behavior law used are then identified, naturally showing a dependence on the material's water content. Numerical calculations are then performed to describe the response of a lap joint assembly. The 1D finite element program (which describes the behavior of the three layers of the assembly in an integrated manner) is first employed, followed by the commercial Abaqus code (with 2D finite elements) for validation purposes, involving the development of a user-defined subroutine (UMAT) for the behavior law. Ultimately, these calculations will be experimentally validated in configurations where the water content (and therefore the mechanical behavior) may be heterogeneous, depending on the diffusion mode observed in the assembly.

## MATERIAL AND EXPERIMENTAL METHODS

In the field of bonded assemblies, the Single-Lap Joint (SLJ - ISO 4587) test is arguably the simplest standardized test to implement, encompassing all the specificities of an assembly in terms of mechanical response (stress/strain heterogeneities, singularities, interfacial adhesion, etc.). This configuration is thus chosen in this study to characterize the mechanical behavior of adhesives within an assembly and the influence of hydric aging. The assembly considered here (symmetric) consists of two metallic steel substrates bonded by a layer of epoxydic adhesive on a surface referred to as the "overlap" area. A planar modelling approach (in the $xy$ plane) is adopted, assuming a uniform depth $p$ (in the $z$ direction), and all data and results are independent of this direction (Figure 1). The overlap length (along the x-axis) is denoted as $L_a$, while the remaining lengths of each substrate are designated as $L_b = L_c$. The thicknesses of the adhesive joint and the two substrates (along the $y$ direction) are respectively represented as $t_a$ and $t_b = t_c$ (Figure 1a). The adhesive and substrates are assumed to be composed of homogeneous and isotropic materials, with the behavior considered as linear elastic for the substrates and elastoplastic for the adhesive. Finally, both ends of the substrates are "fixed" (transverse displacement and rotation constrained), and the left end is fixed longitudinally while the right end is subjected to an axial load F.

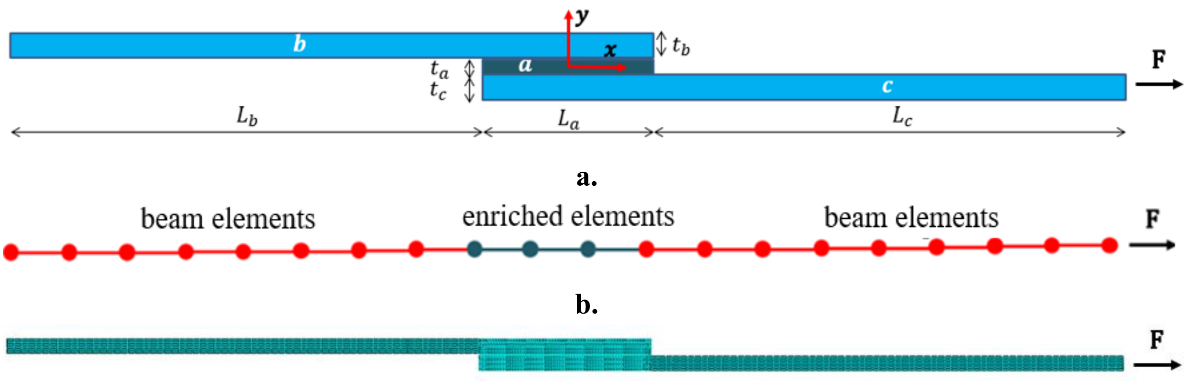



**Figure 1.** Single lap joint configuration: a - geometry and boundary conditions;
b - 1D FE model representation; c - 2D FE model representation (Abaqus)

In the 2D case, the finite element mesh consists of quadrilateral elements with 4 nodes and reduced integration, assuming plane stress for the substrates and plane strain for the adhesive. In the 1D model case (Figure 1b), the substrates are represented by Timoshenko beams, thus considering the effects of transverse shear which can be significant in practice. Instead, the adhesive is modeled as a 2D continuous medium satisfying the assumption of plane deformations (for coherence with the previous 2D modeling). Longitudinal and transverse displacements in this layer are described by polynomials of degree 2 and 3,

respectively, of the position variable through the thickness. In the overlap area, the behavior is integrated (numerically) through the thickness of the three layers (substrate-adhesive-substrate) so that this area can also be described by 1D finite elements. With this approach, all finite elements used (enriched elements or beam elements) are therefore 1D elements, for which quadratic shape functions are chosen (with 3 nodes per element).
The chosen elastoplastic behavior law for the adhesive is a Mahnken-Schlimmer type law, which allows for describing non-associated plastic behavior, with the influence of hydrostatic pressure. The same model has been implemented in the 1D finite element program and within the commercial Abaqus code, through the development of a user-defined subroutine (UMAT). All the calculations are performed under the assumption of small transformations.

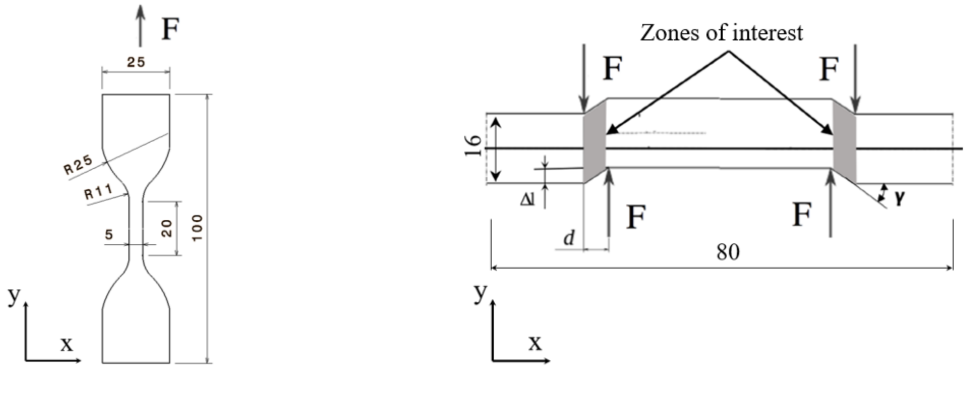
## PARAMETER IDENTIFICATION OF THE MODEL

Identifying the material parameters of the constitutive model used for the adhesive behavior requires a comprehensive database of experimental data based on various types of mechanical tests. This study focuses on the influence of hydric aging on the mechanical behavior of the adhesive under different environmental conditions.
Therefore, bulk samples in both pristine and aged states at two different humidity levels (75% RH and immersion) were tested in tension and shear, employing two setups and thus two types of specimens (Figure 2.). First, the principle of the tension test is to apply a uniaxial load F (Figure 2a) to a sample of constant cross-section. This type of test is fundamental in that it simply provides the uniaxial behavior law (stress-strain curve in uniaxial tension) of the material. The essential mechanical properties (Young's modulus, yield strength, stress at break) are easily identified from such a curve [6,7]. Then, shear test on bulk samples used in this study is adapted according to the work of Ilioni et al. [5,6]. The principle is shown in Figure 2b. From this type of test, we can calculate the shear stress (τ) with equation (1) and the shear strain or half-slip (γ/2) with equation (2):

$$\tau = \frac{F}{S} \text{ with } S = w \times e \tag{1}$$

$$\gamma = \frac{\Delta l}{d} \tag{2}$$

where F is the applied force, S the material cross-section, w and e the sample width and thickness, Δl the top displacement and d the distance between the clamping jaws.
In the literature, one can find several methods of inverse identification for this type of model [1,2]. In this study, a similar approach has been developed for the identification of appropriate parameters. Considering the various aging states of the adhesive, the inverse identification involves a sequential approach here. In each configuration, the elastic parameters are first evaluated, followed by the parameters related to the plasticity criterion, and finally the hardening parameters.




**a.** **b.**

**Figure 2.** Sample geometry (1 mm thickness): a – tensile; b – shear

Figure 3, for example, illustrates the comparison between the experimental results and the numerical results obtained after reverse identification, for different ageing conditions. In each case, the numerical results are in good agreement with the experimental results, demonstrating the quality of the calibration and the selected parameters. It is noteworthy to observe the significant influence of water content on the mechanical response of the adhesive.

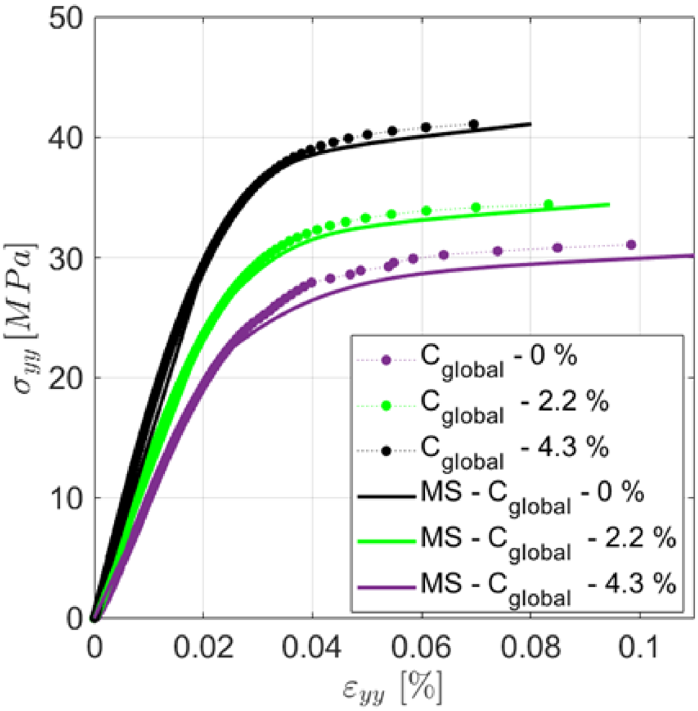



**Figure 3.** Influence of ageing on the mechanical behaviour of adhesive – Longitudinal tensile stress-strain curves

## RESULTS AND DISCUSSIONS

Finally, using the previously identified parameters, numerical simulations of the mechanical behavior of a single-lap joint can be performed, assuming for now a uniform water content throughout the adhesive joint. These calculations are performed with the 1D code, then on Abaqus for comparison. After a preliminary mesh convergence analysis, a discretization of 80 elements along the overlap length and 4 elements through the thickness of the adhesive joint is retained.

**Table 1.** Assembly dimensions

| $p\ (mm)$ | $t_a\ (mm)$ | $t_b = t_c\ (mm)$ | $L_a\ (mm)$ | $L_b = L_c\ (mm)$ |
|---|---|---|---|---|
| 25 | 0.4 | 2 | 24 | 66 |

The geometric parameters considered are presented in Table 1. Finally, a force of 14kN is applied to one of the ends, which makes it possible to obtain a relatively extensive state of plastic deformation within the adhesive joint, without however achieving very high levels of deformation.

In Figure 4, the profiles of the various (planar) components of the stress tensor are plotted along the neutral axis of the adhesive over the entire overlap length (in the immersion-aged state, by way of example). Figure 4b displays longitudinal stresses ($\sigma_{xx}$), Figure 4c shows peel/transverse stresses ($\sigma_{yy}$), and Figure 4d presents shear stresses ($\sigma_{xy}$).

A very good agreement is observed between the 1D curves (MS 1D on the figure), and the reference results obtained from the 2D model (MS 2D on the figure - Abaqus), at least in the central majority part of the curves. Differences between the two formulations, mainly localized at the ends of the adhesive joint, are attributed to discretization issues and also to the integration of the response through the thickness performed for the 1D model.

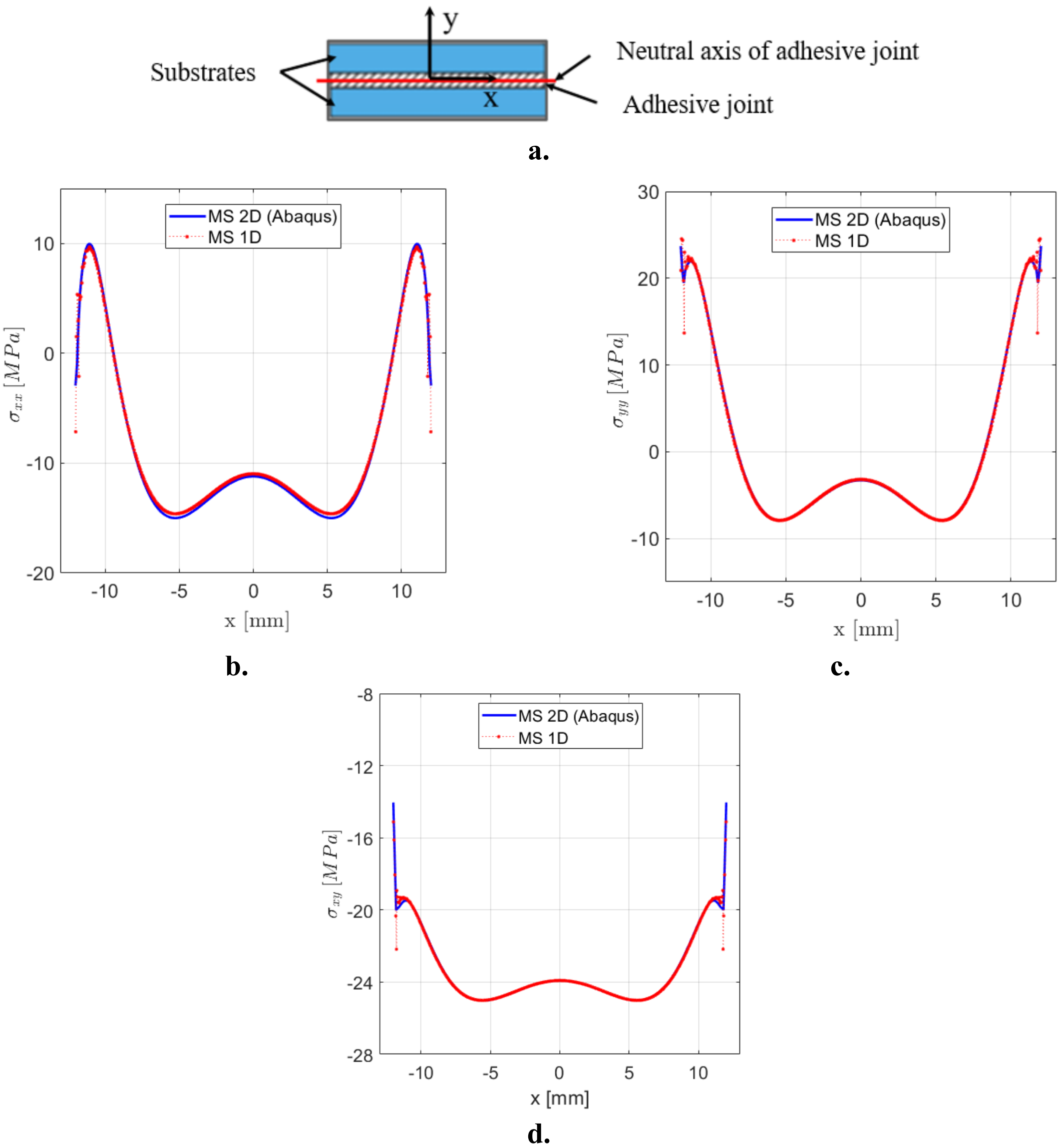



**Figure 4.** Evolution of stress along the neutral axis of the adhesive joint (aged in immersion): a - schematic representation of the analysis area; b - longitudinal; c - transverse; d - shear.

## CONCLUSIONS AND FUTURE DIRECTIONS

This study presents initial results of a general approach aimed at modeling the mechanical behavior of a bonded assembly under the influence of hydric aging. The behavior of the selected adhesive has been calibrated with the same law for different aging levels. An original and effective model of a single-lap joint has been developed to locally account for the influence of water content on the material parameters involved in the behavior description. Results obtained from the simplified modeling were compared to reference results obtained with 2D finite elements using Abaqus software, considering uniform aging for now. The quality of the results is promising and suggests the potential of such a model to predict the actual mechanical behavior of an aged bonded assembly, provided a prior description of water diffusion within the adhesive joint.

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