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NUMERICAL MODELLING OF THE BONDING PROCESS FOR WIND TURBINE BLADES: MODEL VALIDATION

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ABSTRACT

Adhesive is typically used in the joint between the two shells composing a wind turbine blade. The bonding process of a blade can be characterized as a squeeze flow problem where the top shell is forced towards the bottom shell, resulting in a deformation in the adhesive. In this study, a 3-D numerical model is developed in order to analyse adhesive propagation in squeeze flow problems with 3-D flow effects. The model is validated by comparison with an experiment where a rectangular prism shaped adhesive sample is squeezed between two parallel plates. In the numerical model the rheological behaviour of the adhesive is approximated with the Bingham material model. The numerical model is in good agreement with the experimental results. In the future, the model will be used to optimize the bonding process of wind turbine blades, save weight and reduce the levelized cost of energy.

1 INTRODUCTION

Wind turbine blades consist of two large shells that are bonded to each other by the usage of adhesive. Since the assembling process directly influences the bonding quality, it plays a crucial role in a blade's structural reliability. In a blade bonding process, the adhesive is deposited on top of the stationary bottom shell that is resting at the lower mould, which is then exposed to a significant force by the approaching upper mould that is holding the corresponding counterpart. The physical phenomenon occurring in the bonding process is called squeeze flow (SF) where two approaching surfaces are merged together by a force, with adhesive in between. For a satisfying bonding quality, a good understanding of how the adhesives flow during SF is important. The complex geometries at the bonding regions necessitate specific adhesive properties such as the ability of keeping the initial geometry until the bonding process is initiated. Such characteristics are obtained in general by using two-component thermosetting polymers. Being able to predict the flow behaviour of such non-Newtonian polymers will not only increase the quality of the bonding, but also enable optimization of the blade assembly process.

Several authors have analytically and experimentally studied the axisymmetric SF problem e.g. investigated the rheological response of non-Newtonian fluids with no-slip [1-4], partial slip [5] and slip [1, 4, 6] boundary conditions. Some authors studied the influence of surface properties such as plate curvature [7], inclination [8] or plate roughness [9]. In addition, an analysis of the compressive forces acting on the substrate during SF of adhesively bonded joints was performed by Bergomesco et al. [10] resulting in a generalized analytical solution for 3-D problems with non-Newtonian fluids with any initial shape. Compared to the analytical studies, numerical studies of the SF phenomenon with non-Newtonian materials are relatively limited. Karapetsas and Tsamopoulos [11] successfully developed a computational fluid dynamics code for 2-D SF problems with non-Newtonian materials. Similarly, a 2-D finite element solver that accounted for both no-slip and lubricated conditions was developed by Adams et al. [12].

In this study, a 3-D numerical model for SF problems with non-Newtonian fluids is validated by performing a comparison with experiments. The SF experiment that is performed with a two-component thermosetting polymer adhesive is presented first. Subsequently, the finite volume based computational fluid dynamics model is introduced. Finally, the results of the experiments and numerical model are compared.

2 EXPERIMENT

In order to validate the numerical model, three identical SF experiments were performed with two plywood plates covered by foil, see Fig. 1. The width of the upper and lower plate was 80 and 150 mm, respectively. The initial shape of the adhesive was rectangular with a width of 25 mm, a height of 15 mm, and a length of 100 mm. This shape was obtained by the use of a plastic spatula. In the experiment, the plates were initially placed with a 15 mm gap and they ended up with a clearance of 1.3 mm after being forced together with a speed of 5 mm/s. Figure 2 illustrates one of the specimens after the SF experiment.

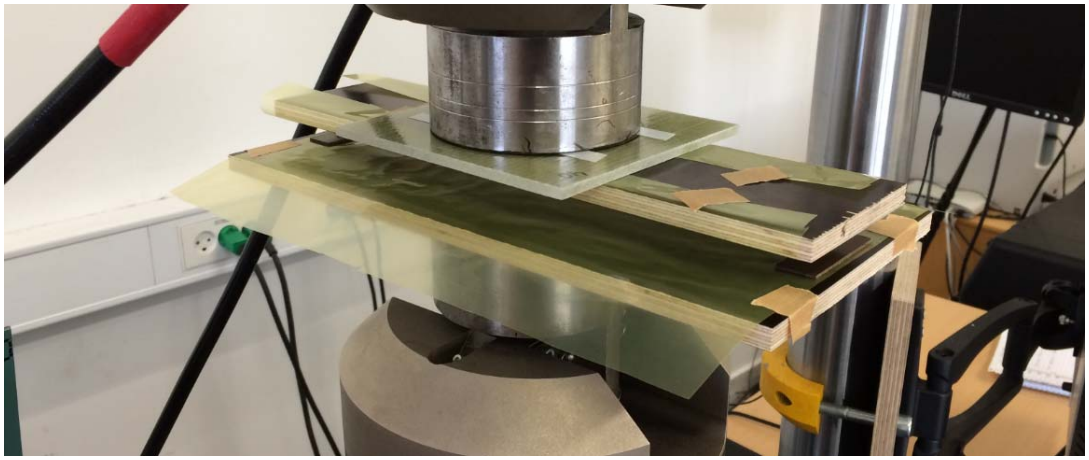

Figure 1: Test setup for the SF experiments.

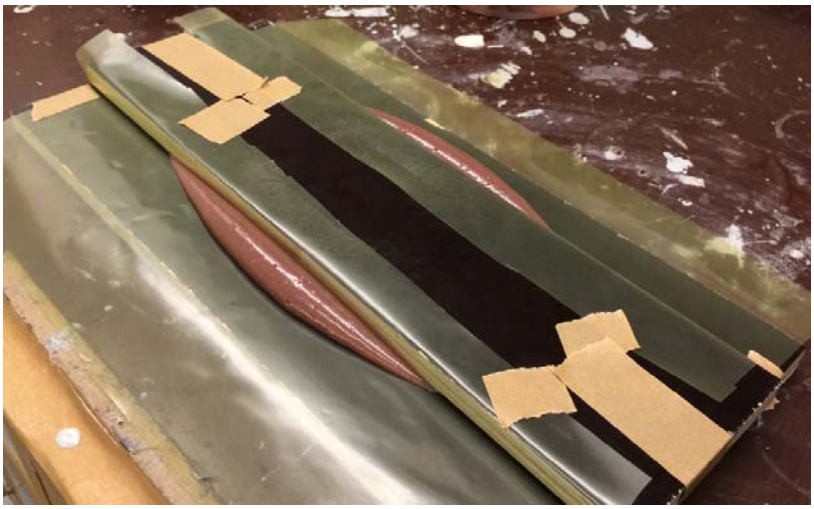

Figure 2: Deformed adhesive after SF experiments.

3 NUMERICAL MODEL

The propagation of the adhesive was modelled in the commercial finite volume based software Flow3D, which previously has been successfully utilized to describe flow of non-Newtonian fluids by the authors [13-15]. The governing equations describing the flow of the adhesive are the continuity equation and momentum conservation equation:

$$\nabla \cdot \boldsymbol{v} = 0 \tag{1}$$

$$\rho\left(\frac{\partial v}{\partial t} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}\right) = -\nabla p + \mu \nabla^2 \boldsymbol{v}, \tag{2}$$

where ρ is the density, $\boldsymbol{v}$ is the velocity, p is the pressure and μ is the dynamic viscosity. The pressure and velocity fields were solved implicitly, and the free surface of the adhesive was tracked with the volume-of-fluid method [16], a very accurate interface tracking algorithm [17]. The plates in the experiment were modelled as rigid solids. A no-slip boundary condition at the plate-fluid interfaces was assumed, while no gravitational effect was taken into account in the model. The non-linear rheological behaviour of the adhesive used in the experiment was approximated by adopting the Bingham material model:

$$\tau = \tau_o + \mu_{pl}\dot{\gamma}, \tag{3}$$

where τ is the shear stress, τ_o is the yield stress, μ_{pl} is the plastic viscosity, and $\dot{\gamma}$ is the shear rate. The material constants given in the specification of the applied adhesive was implemented into the numerical model, see Tab. 1. Note that, as the yield stress was not specified, it was instead estimated. In addition, the influence of the hardener on the rheological properties was neglected, as the mixing ratio was very low and the gelation time was long.

Density [kg/m^3]	Viscosity [mPa.s]	Yield stress [Pa]
1100	700	200*

Table 1: Material constants for the adhesive. (*) Is an estimated value

4 RESULTS

In Fig. 3, the final geometry of one of the specimens is illustrated, while Fig. 4 shows the corresponding final geometry predicted by the numerical model. [A], [B], [C] and [D] correspond to the total length, squeeze-out length, width, and height of the final shape of the adhesive, respectively. Tab. 2 shows the geometrical comparison between the experiments (average values) and the 3-D numerical model.

Figure 3: Final geometry of the specimen after SF experiment.

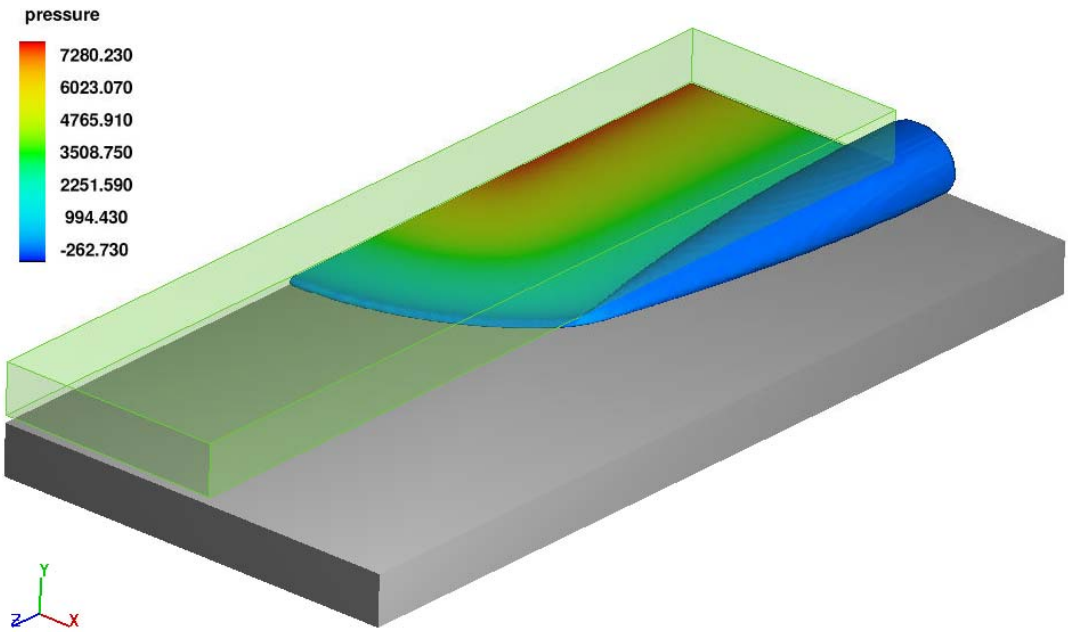

Figure 4: Prediction by the 3-D numerical model.

	Experiment	3-D Model
Total length (A) [mm]	202	186
Squeeze-out Length (B) [mm]	170	150
Width (C) [mm]	116	104
Height (D) [mm]	7	10

Table 2: Geometrical comparison between experiments and numerical results.

Generally, it can be stated that the predicted results are in good agreement with the experimental results. The predictions are approximately 8 % smaller for the total length, maximum squeeze-out length, and width. This difference may be the result of not obtaining a perfect initial shape of the adhesive in the experiments. The discrepancy in heights might be a result of the fact that the experimental samples are exposed to the gravitational force for a periode of time before the onset of curing i.e. obtaining their final geometry.

5 CONCLUSIONS

The results of the numerical model were in good agreement with the experimental data. The largest discrepancy between the two was related to the height of the adhesive, but this is expected to be a consequence of the experimental samples deforming due to gravity before obtaining their final geometry. In the future, the developed 3-D numerical model will be used to optimize the bonding process of wind turbine blades, e.g. by reducing the risk of obtaining zones with no adhesive in the joint or by minimizing cost/waste and mass of the blade.

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