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► **To cite this version:**

Jérémie Vignes, Fabrice Schmidt, Gilles Dusserre, Olivier de Almeida, Jean Frederic Dalmasso. Numerical simulations of clay tiles compression. ESAFORM 2012 - 15th International ESAFORM Conference on material forming, Mar 2012, Erlangen, Germany. pp.1403-1408, 10.4028/www.scientific.net/KEM.504-506.1403 . hal-01687321

HAL Id: hal-01687321

<https://hal.science/hal-01687321>

Submitted on 6 Mar 2019

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Numerical simulations of clay tiles compression

VIGNES Jérémie^{1, a}, SCHMIDT Fabrice^{1, b}, DUSSEYRE Gilles^{1, c}, DE ALMEIDA Olivier^{1, d} and DALMASSO Jean Frédéric^{2, e}

¹Université de Toulouse ; Mines Albi, INSA, UPS, ISAE, ICA (Institut Clément ADER) ; Campus Jarlard, F-81013 Albi cedex 09, France

²CRED TERREAL, Route de Revel, 11400 CASTELNAUDARY

^ajeremie.vignes@mines-albi.fr, ^bfabrice.schmidt@mines-albi.fr, ^cgilles.dusserre@mines-albi.fr, ^dolivier.dealmeida@mines-albi.fr, ^ejean-frederic.dalmasso@terreal.com

Keywords: Clay, free compression test, rheological behaviours, friction law, inverse analyse, forming simulation.

Abstract: During the pressing step, the clay tiles undergo stresses which result in the appearance of defects. A rheological study, based on free compression tests, allowed to confirm the Elasto-viscoplastic behaviour of the clay. The different constitutive parameters were estimated by fitting the force-displacement experimental curves using the optimisation algorithm (ES Metamodel) implanted in the commercial software Forge 2009®. The influence of the tribological parameters was studied using squeezing numerical simulations of a full tile. The numerical model was validated with experimental squeezing test of technological specimen with a tile lug. Then, we have compared experimental force with the numerical one and deduced that the clay/tool interface is not perfectly sliding. A friction Tresca's law was used to model the clay/tool interface. Numerical results showed that the actual geometry of tile lug didn't allow to form correctly the tile. Several areas undergo tensile stress, air traps, ... A new geometry of tile lug was proposed in order to limit this phenomenon. Using a simplified defect criteria (Latham and Cockroft), the numerical model allowed to locate the areas where there is a risk of crack.

Introduction

During the shaping of a clay tile by pressing, the clay undergo stresses which can have for consequence the appearance of cracks, pulling out, and distortion. The manufacturing process of clay tiles can be divided into five steps: preparation of the raw material, extrusion, pressing, and finally drying and cooking. It is necessary to limit the appearance of defects in order to improve the yield of the process. In this paper, we will present a study which aims to determinate the tribo-rheological behaviour of the clay used to produce tiles. Numerical simulation is performed to understand the phenomenon leading to the appearance of defects. The study focuses on the understanding of phenomenon involved in the third step. There are different types of tests to identify the behaviour of the clay. There are the methods originate of the ground mechanical [1] and the fluid mechanical [2]. Like explained in the thesis of E. Foudrinier [3], it is essential to choose a test involving a state of stress representative of the actual geometry to determinate the behaviour of the clay. For example, a capillary rheometer was used to study the extrusion step. We decided to use a squeeze flow test [4, 5] on a clay cylindrical sample to find the rheological behaviour. This test can be easily modelled by a 2D axisymmetric model. The analytical solutions given by Engmann [6] allowed to calculate the pressing strength according to the different parameters of the behaviour laws. The SE metamodel algorithm [7] available in the optimization module of the commercial software Forge 2009® allowed to identify the parameters of the constitutive law. The element deletion method [8] implemented in the software Forge 2009® is based on a critical value of the Latham & Cockroft [9] criteria. The simulation performed by using the identify behaviour and damage models.

Identification of the constitutive law

A squeeze flow test was used to determine the parameters of the constitutive law. This test involved a state of stress similar to those involving in the pressing step. The identification of the rheological parameters is complex because it requires to identify the friction law at the same time. To get around this problem, the pressing plates were modified in order to ensure a totally sticky contact. The tests were performed on an electro-mechanical testing machine, with a load cell 30 kN. To analyse a wide range of speed strain rates, we used several crosshead displacement rates. The clay samples were cylindrical. The dimension can't be given in this article for confidential reason. As it can be seen on the figure 1, the tested clay shows an Elasto-visco-plastic behaviour. The instantaneous answer of the material is linear and is supposed to follow the generalized Hooke's law (eq 1) until the flow stress is reached.

$$\bar{\epsilon}_E = \frac{1+\nu}{E} \bar{\sigma} - \frac{\nu}{E} \text{tr}(\bar{\sigma}) \bar{\mathbf{I}} \quad (1)$$

The clay follows then a visco-plastic behaviour. The evolution law of the flow stress is given by (eq 2).

$$\bar{\sigma} = \sigma_0 + \sqrt{3}K_0(\bar{\epsilon}_V)^n(\sqrt{3}\dot{\bar{\epsilon}}_V)^m. \quad (2)$$

An inverse analysis was carried out to obtain the different parameters of the constitutive law using the optimisation module of the commercial software Forge 2009[®]. The optimisation algorithm is based on a metamodel assisted evolution strategy. The rheological parameters identified were the Young's modulus, the consistency, the sensitivity with the strain rates and the sensibility with the strain hardening. The Poisson's ratio was fixed at 0,45, like it is commonly given in the literature. A set of parameters was identified for each crosshead displacement rate. The mean value of each evaluation was finally calculated for each parameters in order to take into account the whole experimented strain rate range. For confidential reason the final parameters can't be given. Strain rate and hardening sensitivity parameters are low. However, if these parameters are neglected, the numerical strength / displacement curve diverges from the experimental curve.

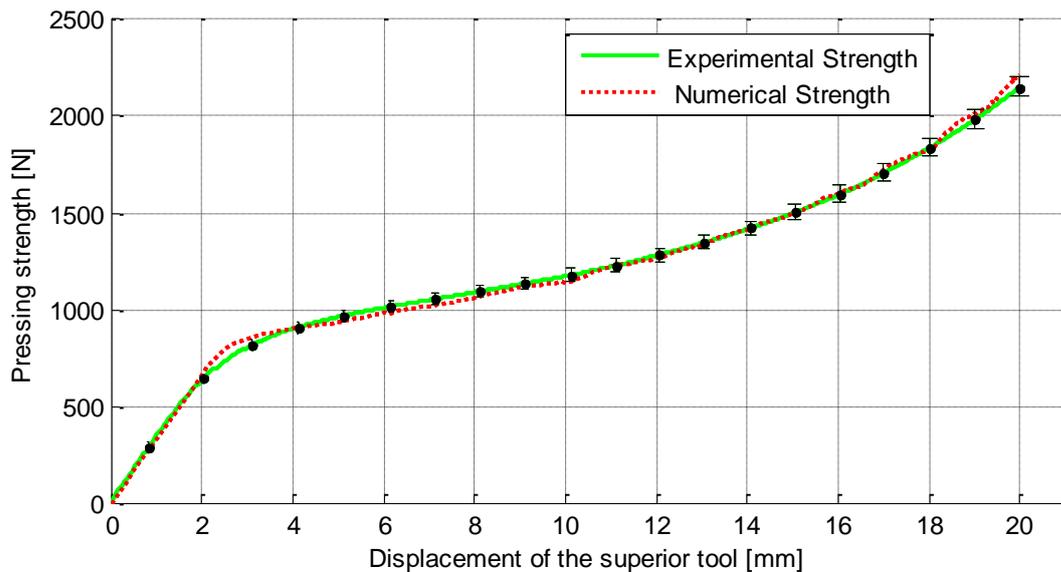


Figure 1: Experimental and numerical strength / displacement curves of a free compression test on a clay sample

The figure 1 compare the experimental strength / displacement curves to the simulated one obtained with the identified set of parameters. The experimental curve is given with the minimal and the maximal values measured during 5 tests in the same conditions. We can notice that the repeatability

of the test is quite good. The quality of the model given by the optimisation algorithm can be controlled with the calculation of the quadratic gap between the two curves. For the model presented, the mean quadratic gap was about three percent.

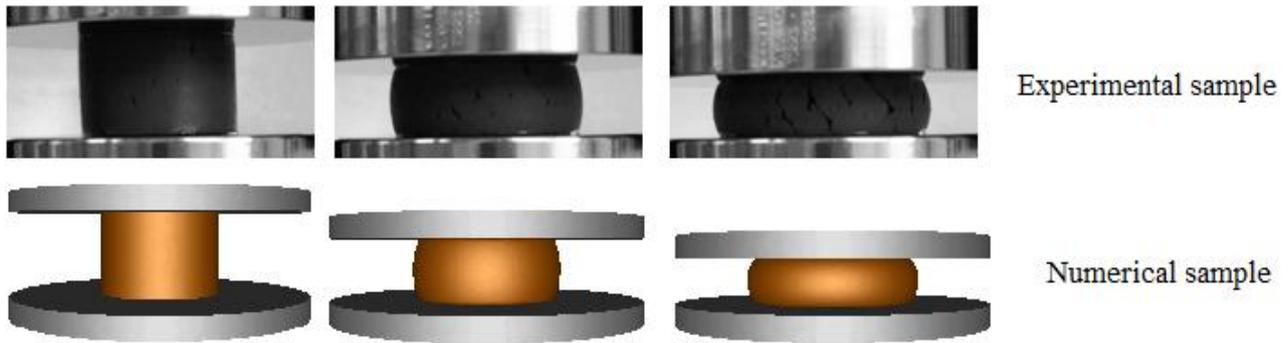


Figure 2: Experimental and numerical compression test on a clay sample

The Figure 2 shows the evolution of a cylinder clay sample during a numerical and experimental free compression test. In this case the friction between the sample and the pressing plates was greased. The numerical model allows to find the evolution of the convex of the sample.

Modelling of the damage during the free compression test

To model the damage observed during the pressing test and introduce into the numerical simulation an element deletion method, available in Forge 2009[®], was used. This technique compares the value of a damage criterion calculated in each element to a limit value corresponding to the occurrence of the failure. If the criterion value is higher than this limit value, the element is automatically deleted. We chose the Latham and Cockroft criterion C defined by (eq 3) where $\bar{\epsilon}_R$ is the plastic strain, $\sigma_I, \sigma_{II}, \sigma_{III}$ are the principal stresses, $\bar{\sigma}$ and $\bar{\epsilon}$ are respectively equivalent stress and strain.

$$C = \int_0^{\bar{\epsilon}_R} \frac{\text{Max}(\sigma_I, \sigma_{II}, \sigma_{III})}{\bar{\sigma}} d\bar{\epsilon}. \quad (3)$$

For each test, the sample height H_d , where the material begin to damage has been measured. The critical value defined by the value of the criterion is reached in the simulation when the height of the sample is H_d . Whereas damage begin to occur on material heterogeneities, the model describes an heterogeneous criterion field due to finite element discretization. The result is then very sensitive to the mesh size, and a very fine mesh is necessary to provide a crack pattern similar to the experimental one. Moreover, the element deletion method is not well suited to model the crack propagation because of a bad evaluation of the stress concentration at the head of the crack. It results in a fracture pattern not so sharp as observed experimentally.

Determination of the friction parameter

It is quite difficult to identify the friction parameter from a free compression test. The analyse of the evolution of the sample profile could be used to determinate the friction parameter but this method is difficult to set up. We decided to use an inverse analyse on a new compression test. For this test, we pressed a small clay sheet in a prototype reproducing the strains involved in the forming of a real tile.

The geometry of the tools allows to stamp a tile lug in the sample. The tools and the clay sample are presented in the figure 3.

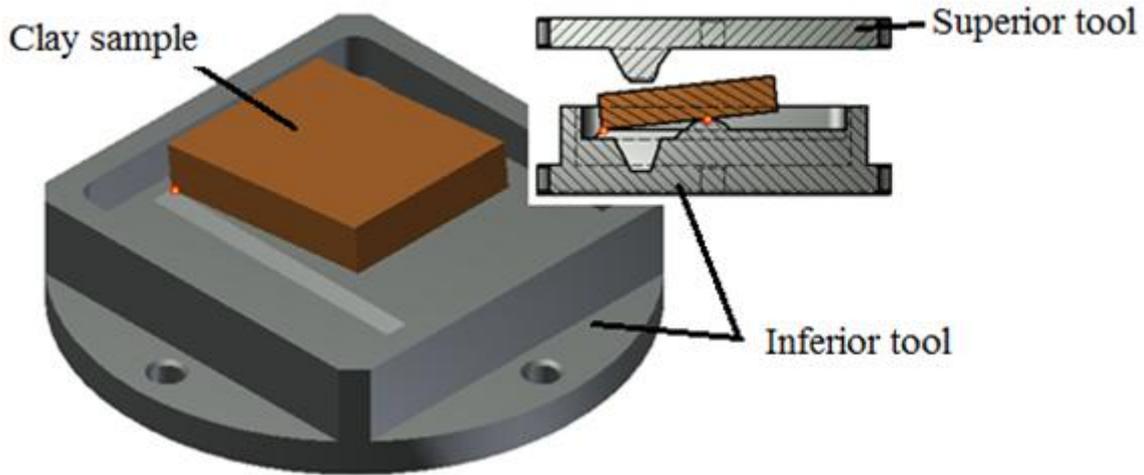


Figure 3: Pressing tools and clay sample used to identify the friction law

The tools were made with stainless steel.

The geometry of the tools allows to stamp a parallelepiped sample. The tools were made with stainless steel. The areas in contact with the clay were polished to obtain the same state of surface like the industrial tools. To model the friction behaviours between the clay and the steel, we decided to use a Tresca law :

$$\tau = -\bar{m} \frac{\sigma_0}{\sqrt{3}} \frac{\Delta \vec{V}}{\Delta V} \quad (12)$$

The inverse analyse allowed to identify a Tresca parameter corresponding to an imperfectly sliding contact. The figure 4 show the strength / displacement curves obtained for the new test. We can observe that the numerical strength curve was positioned in the dispersion range of the experimental strength curve. The numerical model allow to reproduce different steps of the pressing test

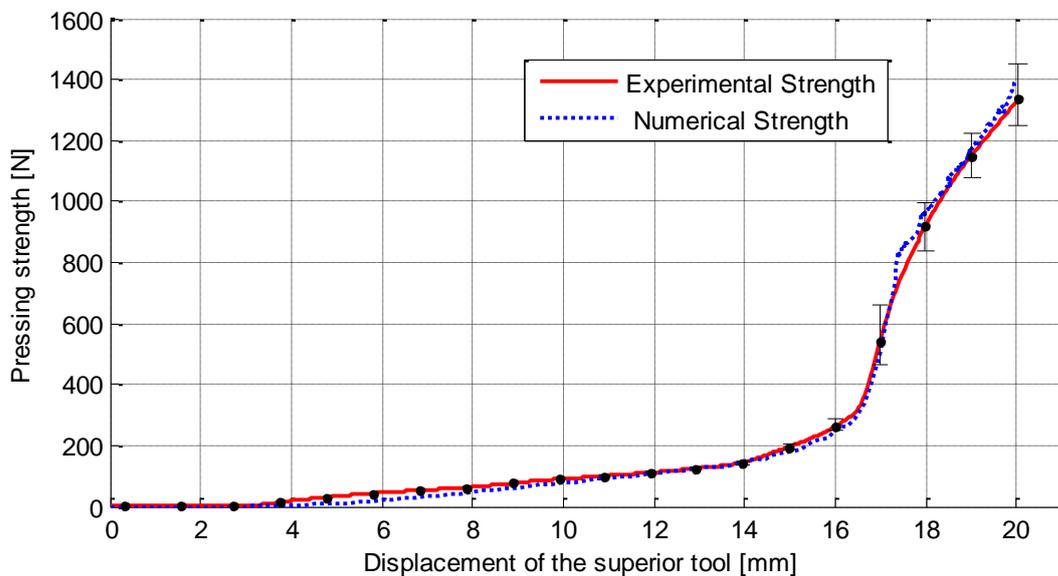


Figure 4: Experimental and numerical strength / displacement curves of a free compression test on a clay sample

Validation of the numerical model with a specific specimen

We have identified the different parameters of the rheological behaviours and damage laws (with the free compression test) and the friction law (with the prototype pressing test). Now, we can use the numerical model to reproduce the prototype pressing test by taking into account the damage.

The numerical model reproduces correctly the geometry of sample. This helps us to validate the different parameters determined. The Mises equivalent stress field (figure 3) helps to define the critical areas on the tile. The figure 5 illustrate that the sharp edge, in the lower face of the lug, will be difficult to form without damage.

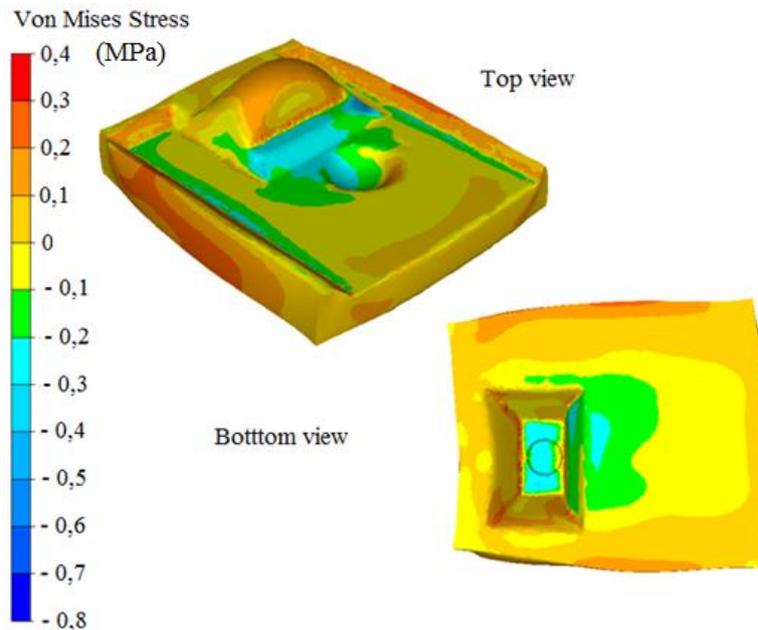


Figure 5: Mises stress field on the clay sample at the end of the test

The damage begins in the same time on the numerical and the experimental sample. The crack appears on the top of the lug. The thinning areas are favourable to tears. Nevertheless, the numerical model does not reproduce perfectly the actual behaviour of the material. The deletion element method creates a loss of material during the pressing. The strength obtained with the numerical model, when the damage is taken into account, is lower than the actual strength. Furthermore, it is necessary to mesh the part with very fine elements. This is why we have used an automatic remeshing during the pressing. When the criterion of Latham and Cockroft, on an element, was near the critic value, this element was divided into ten small elements. This allowed to limit the loss of volume. The major problem of this method is the dramatic increase of the computation time.

Conclusions and perspectives

This study allowed to develop a methodology to identify the different parameters of the constitutive law of the clay. Estimating a single friction parameter from a complex test allows to obtain a mean value taking several contact conditions involved in the actual process. Moreover, it allows to discriminate visually and classify the different clay available according to their capacity to result to a plastic forming.

The influence of the tribo-rheological parameters was put in evidence with the numerical simulation of a clay tile forming. The friction law plays a lot in the forming quality. When the clay slide in the tool, the tile is correctly formed but when there are some adhesion areas, the clay is cut through. This leads to the creation of damage areas.

The numerical simulation will be a new solution to improve the actual geometry of the tiles. The commercial software Forge 2009[®] can supply a map representative of the state of internal stress. This will allow to develop new tools and new geometries to increase the yield of the process. Indeed, the analyse of the numerical stress fields helped to divided by two the internal stress at the end of the pressing step.

Acknowledgements

The present study was supported by Terreal company. The authors wish to acknowledge this industrial partner for this support and his help.

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