M 14. TOWARDS A MULTI-ELEMENT SIMULATION OF HEAVILY OVER-CONSOLIDATED BAGASSE USING A MATERIAL SUBROUTINE

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Abstract

A better understanding of the behaviour of prepared cane and bagasse, and the ability to model the mechanical behaviour of bagasse as it is squeezed in a milling unit to extract juice, would help identify how to improve the current process. There are opportunities to decrease bagasse moisture from a milling unit. The behaviour of bagasse in chutes is poorly understood.

Previous investigations have shown that juice flow through bagasse obeys Darcy's permeability law, that the grip of the rough surface of the grooves on the bagasse can be represented by the Mohr-Coulomb failure criterion for soils, and that the internal mechanical behaviour of the bagasse is critical state behaviour similar to that for sand and clay.

Progress has been made in the last 11 years towards implementing a mechanical model for bagasse in finite element software. The objective is to be able to correctly simulate various simple mechanical loading conditions measured in the laboratory. Combining these behaviours together is thought to have a high probability of reproducing the complicated stress conditions in a milling unit. This paper reports on progress made towards modelling the fifth and final (and most challenging) of the simple loading conditions: the shearing of heavily over-consolidated bagasse, using a specific model for bagasse in a multi-element simulation.

Introduction

The crushing of prepared cane and bagasse in a milling unit to remove sugar and water involves large deformations with decreases in volume by a factor of seven. The compression pressures range from a few kilopascals at the feed (Donnelly) chute to as much as 20 000 kPa at the delivery nip. The bagasse material and its contact with the roughened surface on the roll grooves are able to sustain large shear stresses in order to feed the material through the roll nips. A milling model incorporating a material model that can reproduce this behaviour is seen as the most promising avenue to make a sizeable, step improvement to the crushing process. Improvements could be made, for example, to reduce bagasse moisture or increase extraction. With a generally increased interest in cogeneration in Australia, and a move towards cane diffusers overseas, the efficient dewatering of bagasse becomes more important.

Based on a material model described by de Souza Neto *et al.* (2008), a progression of papers has been presented to the ASSCT on developing a mechanical material model specific to bagasse by comparing predictions for simple loading conditions (Plaza, 2010, 2011, 2012) against measurements (Plaza, 2002), with the latest paper being submitted to the ISSCT (Plaza, 2013). The model under modification was tested against the following five loading conditions on bagasse deemed to be important for modelling bagasse behaviour in a milling unit:

1. initial loading in compression
2. unloading in compression
3. reloading in compression
4. shearing of normally consolidated bagasse
5. shearing of heavily over-consolidated bagasse.

A single element model was used for the comparison. For the first four loading conditions, a single element is adequate as the material is expected to behave uniformly, and good reproduction was predicted (volume with changing vertical stress for the first three, and shear stress and volume with changing shear strain for the fourth). For the fifth loading condition, Plaza (2013) used a single element model and a parameter estimation package called PEST (Anon., 2012a) to conclude that the existing model was likely to be able to achieve good reproduction of the shear behaviour of heavily over-consolidated bagasse, including volume change, before the peak stress was reached. This is noted to be an important development as predicting shear stress and volume change simultaneously as shear strain proceeds had previously been problematic. However, for the modelling of the shear behaviour of heavily over-consolidated bagasse, a multi-element model is required close to and after reaching the peak shear stress, as non uniform behaviour is expected. Ultimately, only a multi element model, such as a Finite Element Model (FEM), can simulate the behaviour of bagasse in a milling unit.

By coding a material model into a subroutine attached to a commercial FEM software package, it is possible to modify any part of the predicted material behaviour, while being able to track and understand the internal workings of the code by, for example, printing out certain variables as the simulation progresses, and still use the solution procedures of a commercial FEM package. This avenue is seen as the best pathway towards achieving an adequate material model for bagasse.

Available FEM software and issues for development of a material subroutine

There are a large number of FEM structural analysis packages available, including open source, semi-commercial software being developed at universities, and fully commercial packages which have student and research options. Four commercial packages that have features desirable for bagasse modelling are ABAQUS (Anon., 2012b), ANSYS Structural and LS-DYNA (Anon., 2012c) and NASTRAN (Anon., 2012d). The software which has been used previously for milling is ABAQUS (see for example Kent, 2004) and its use has been continued in this study. As with many other software packages, ABAQUS has two solution options, implicit (known as standard) and explicit. The implicit (standard) version does have capability to model large deformations. However, the explicit method is usually more suitable when simulation of large deformations and/or impact is required.

The different way in which material subroutines are handled by the implicit and explicit versions is relevant to the current purpose of developing a material subroutine:

- For the implicit version, the user-defined material model is implemented in the user subroutine UMAT. ABAQUS supplies current stresses and strains, and change in strains, to UMAT. Solution dependent state variables can also be supplied, as defined by the user (for example, the degree of over-consolidation of the material). UMAT calculates an updated material stiffness matrix, and has the opportunity to update and return stresses, strains and solution dependent state variables to ABAQUS. Importantly, ABAQUS requires the user subroutine to provide it with an updated consistent material stiffness matrix. This requirement is mathematically challenging to implement for a relatively complicated elasto-plastic model as required for bagasse.

- For the explicit version, the user-defined material model is implemented in the user subroutine VUMAT. ABAQUS supplies current stresses and change in strains to VUMAT. Solution dependent state variables can also be supplied. VUMAT calculates an updated material stiffness matrix, and has the opportunity to update and return stresses and solution dependent state variables to ABAQUS. ABAQUS does not require the user subroutine to provide it with an updated consistent material stiffness matrix.

It was concluded from the above requirements that ABAQUS Explicit was a more friendly option to begin the task.

Description and progress in multi-element modelling

The ABAQUS Explicit model that was built is shown in Figure 1. It shows two side walls, a bottom wall, and a steel plate made up of 50 slender looking elements pushing on top of a bagasse material made up of 650 elements. Both the steel plate and bagasse were meshed with CPE4R elements, which are often used in the simulation of metal forming processes, and are suitable for modelling of the current problem. The CPE4R is a two dimensional, four-node bilinear uniform strain (one integration point per element), plane strain, quadrilateral, reduced integration and hourglass control element. There is a gap of 3 mm between each side wall and the bottom wall. The walls were defined as analytical surfaces. The bottom wall is initially located such that it will move from right to left and induce shear on the bagasse elements in contact with it, while maintaining a surface underneath the box at all times. The dimensions of the initial block of bagasse were 280 mm wide by 41 mm high. The dimensions reflected those achieved in a laboratory test after initial vertical compression, unloading and holding the top steel plate at the required vertical pressure, and just before the shear strain was applied by moving the bottom wall horizontally.

The steel plate was modelled as an elastic material, with the uniformly applied stresses in this simulation resulting in very small strains in the steel plate.

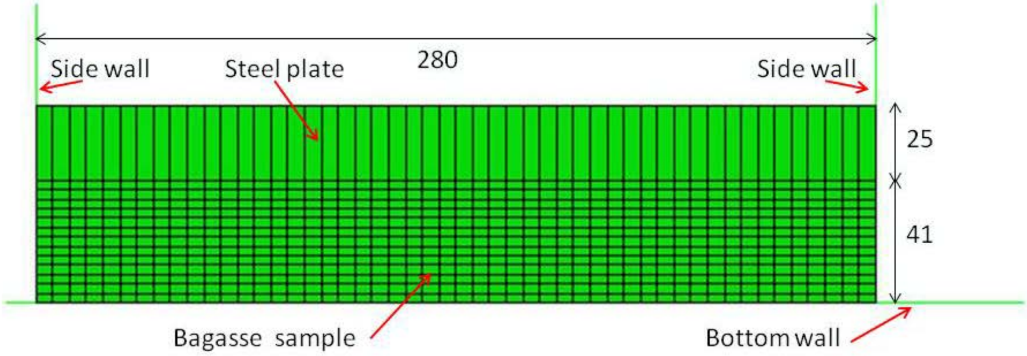

Fig 1 – ABAQUS Explicit multi-element model geometry (dimensions in mm).

The bagasse elements were defined using the equations and properties described in Plaza (2013) for an elasto-plastic critical state material model. The elastic behaviour was modelled using the following equations and the parameter values reproduced in Table 1.

$K = \sigma_s (1 + e) / \kappa$ (1) (Naylor and Pande, 1981)

$E = 3 K (1 - 2\nu)$ (2) (Naylor and Pande, 1981; Muir Wood, 1990)

$G = E / (2 (1 + \nu))$ (3) (Timoshenko and Goodier, 1982; Muir Wood, 1990)

where K is the bulk modulus, G is the shear modulus, E is Young's modulus, ν is Poisson's ratio, κ is the slope of the elastic unloading-reloading line when void ratio is plotted versus the natural log of applied pressure, e is void ratio and σ_s is the confining stress.

Table 1 – Parameters used in simulation of shearing of heavily over-consolidated final bagasse

λ	κ	ν	M	β_1	p_t (kPa)	ψ	β_2	f1	f2
0.93	0.169	0.06	1.45	0.71	6.0	1.57	1.03	0.74	2.0

It is noted that for the case modelled the yield and potential surfaces were different. The yield surface is defined by the values of M (the slope of the critical state line) and β_1 (beta modification for the shape of the yield surface) and the potential surface is defined by ψ (the dilation angle) and β_2 (beta modification for the shape of the potential surface). The slope of the normal compression line is denoted by λ. As per previous simulations, P_t is a small tension (or cohesion) stress of 6.0 kPa. There are two adjustment parameters, f1 and f2. The role of f1 is to adjust the magnitude of the specific volume change due to the shear strain. The role of f2 is to adjust the shear stiffness. As noted by Plaza (2013), whether these two parameters are actually required is to be confirmed in a future study.

The explicitly defined maximum values of coefficient of friction of the bagasse were 0.3 on the vertical side walls, and 1.4 on the pushing steel surface and the sideways moving bottom wall. These correspond respectively with measured values achieved on a smooth mild steel surface, and a grooved surface (5 mm high grooves at 90 degree included angle) at similar pressures, reflecting the test laboratory equipment used for the test under simulation (Plaza, 2002). Should the forces parallel to the surfaces reach values requiring higher coefficients, then slip of the bagasse on the corresponding surface should be predicted by the simulation.

The initial vertical stress before shearing was applied was 340 kPa, with a K_o of 0.4, resulting in initial lateral stresses of 136 kPa. The initial stress history reflected an over-consolidation ratio of approximately 5.0, that is, heavily over-consolidated. Figure 2 shows the predicted vertical stress (kPa) with an initial application of vertical pressure of 340 kPa. The values in all elements are close to the applied value. The simulation is in equilibrium and was achieved by ABAQUS after 3267 increment calls for each bagasse element to the VUMAT subroutine. The strains in the bagasse sample at this stage were insignificant.

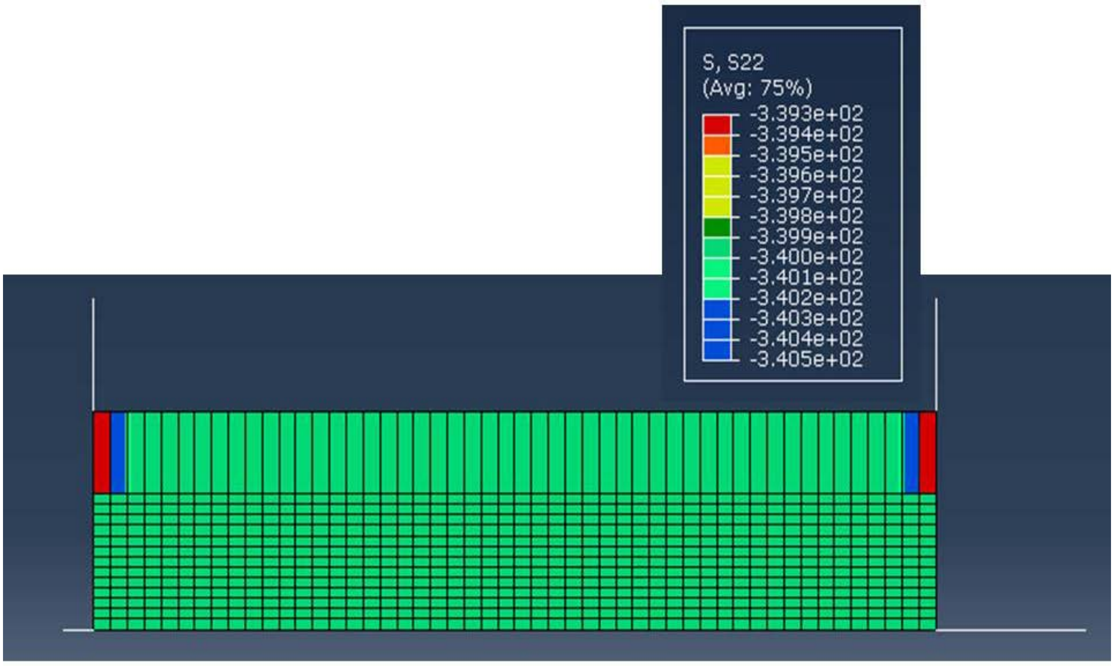

Fig 2 – Simulation with an initial application of a vertical pressure of 340 kPa on the steel plate.

In the next simulation step, the bottom wall was then moved sideways. The prediction was achieved by ABAQUS after 5881 increment calls for each bagasse element to the VUMAT subroutine, after which ABAQUS crashed. Figure 3 shows the predicted vertical stress, while Figure 4 shows the predicted shear stress, at a horizontal displacement of the bottom wall of 6 mm to the left. The predicted deformation of the elements is also shown. Figure 5 shows close up views of the predicted shear stress for the left and right sides of the model.

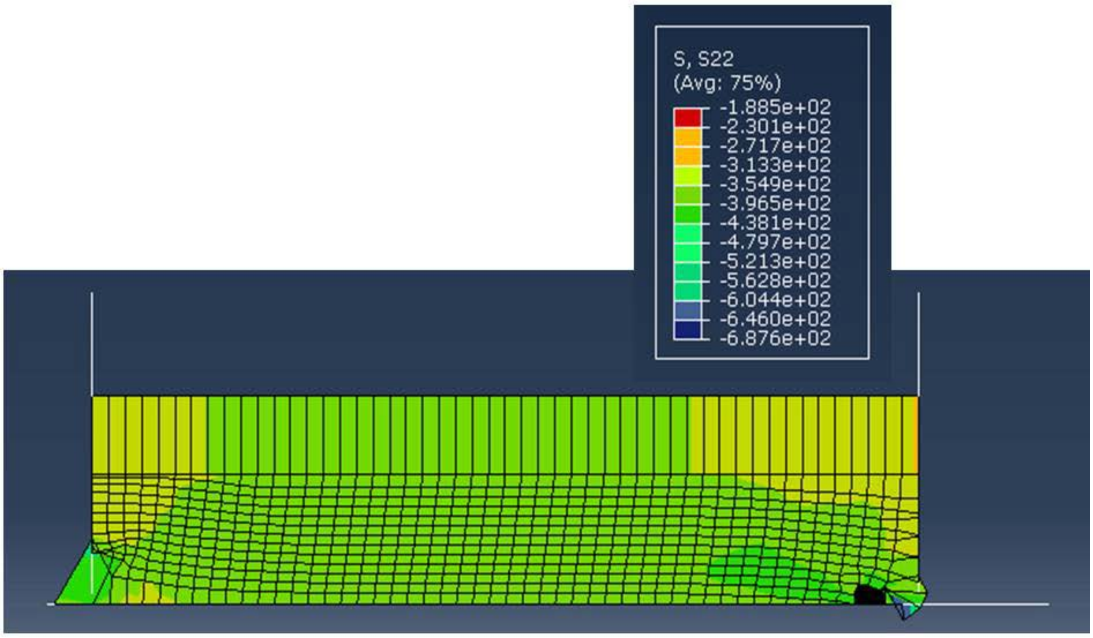

Fig 3 – Predicted vertical stress (kPa) at a horizontal displacement of the bottom wall of 6 mm.

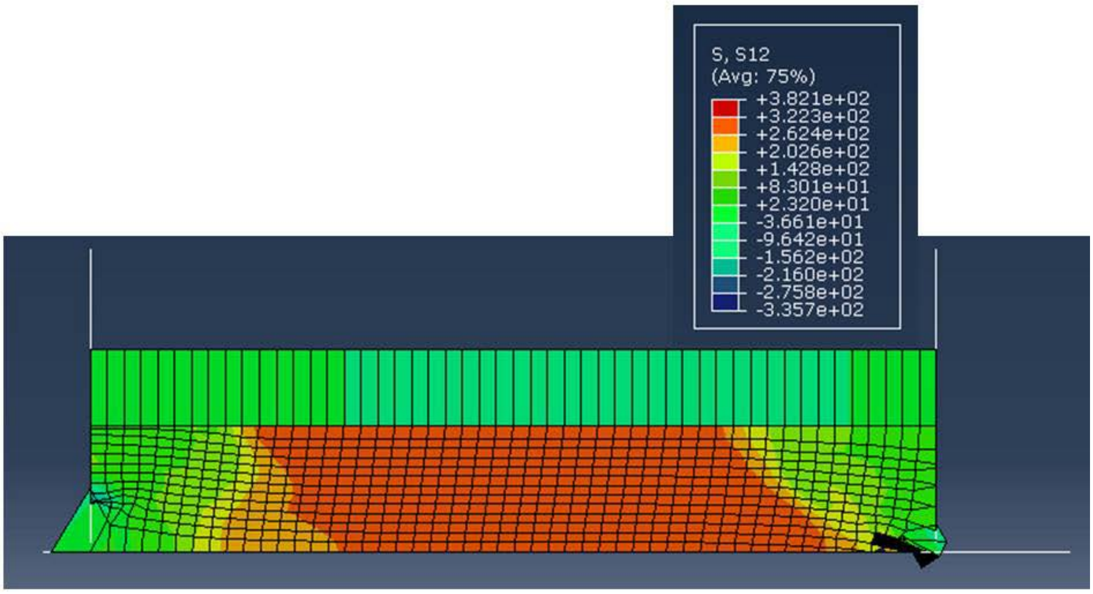

Fig 4 – Predicted shear stress (kPa) at a horizontal displacement of the bottom wall of 6 mm.

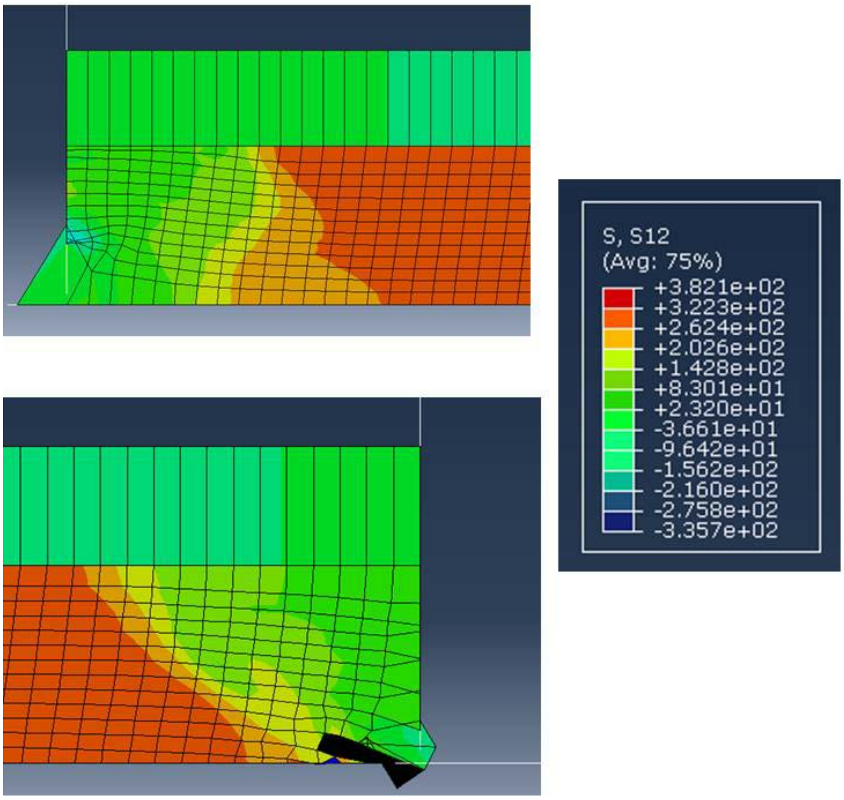

Fig 5 – Close up views of the predicted shear stress (kPa) at the left and right sides of the model at a horizontal displacement of the bottom wall of 6 mm.

On initial inspection, the predictions of vertical pressure and shear stress look reasonable, with a uniform distribution in the middle of the sample and becoming non uniform near the left and right walls. However, on closer inspection, it is seen that the bagasse has not moved away from the right wall as expected. On the left side, near the steel plate elements, the bagasse elements have flattened out, which is also believed to be wrong. The gross element deformations at the bottom corners of the bagasse material are expected, and, even if correct, need some kind of mesh adaptation option to be added to in the ABAQUS simulation procedure.

The predictions shown above were achieved after a significant effort in developing the procedures required by ABAQUS. During the simulation ABAQUS provided a myriad of warnings and suggestions on how to improve the simulation, which are still to be fully adopted. The VUMAT subroutine needs further development, for example, for a material like bagasse which changes volume both in compression and shear, a strain feedback needs to be provided back to ABAQUS Explicit. While there are obvious deficiencies, the results are thought encouraging though significantly more effort would be required for both the ABAQUS procedures and the material subroutine to provide meaningful predictions for a multi element simulation using an external subroutine.

Conclusions

It is believed that an improved understanding of bagasse mechanical behaviour and improved modelling capability is required to achieve further gains in milling in a logical, structured manner. By coding a material model into a subroutine attached to a commercial FEM software package, it is possible to modify any part of the predicted material behaviour, while being able to track and understand the internal workings of the code, and still use the solution procedures of a commercial FEM package. This avenue is seen as the best pathway towards achieving an adequate material model for bagasse. This paper has made significant progress towards modelling the behaviour of bagasse in a multi element model using an external material model subroutine, and the modelling details and current results have been reported. More development is required to provide meaningful predictions.

REFERENCES

Anon. (2012a) PEST: Model-independent parameter estimation & uncertainty analysis. http://www.pesthomepage.org/Home.php (accessed 4 January 2012).

Anon. (2012b) ABAQUS: Explicit user's manual, version 6.12.1. Dassault Systemes Simulia Corp.: Providence, RI, USA.

Anon. (2012c) ANSYS. http://www.ansys.com (accessed 20 November 2012).

Anon. (2012d) NASTRAN. http://www.nenastran.com (accessed 20 November 2012).

Kent GA (2004) Predicting mill speed. *Proceedings of the Australian Society of Sugar Cane Technologists* **26**, (electronic format) 10 pp.

de Souza Neto EA, Peric D, Owen DRJ (2008) 'Computational methods for plasticity: theory and applications'. (John Wiley & Sons Ltd: Chichester).

Muir Wood, D (1990) 'Soil behaviour and critical state soil mechanics'. (Cambridge University Press: UK).

Naylor DJ, Pande, GN (1981) 'Finite elements in geotechnical engineering'. (Pineridge Press: Swansea, UK).

Plaza F (2002) Measuring, modelling and understanding the mechanical behaviour of bagasse. PhD Thesis, University of Southern Queensland, Toowoomba.

Plaza F (2010) A further step in the modelling of the mechanical behaviour of bagasse. *Proceedings of the Australian Society of Sugar Cane Technologists* **32**, 621-628.

Plaza F (2011) An additional step towards modelling the mechanical behaviour of sugar cane bagasse. *Proceedings of the Australian Society of Sugar Cane Technologists* **33**, (electronic format) 5pp.

Plaza F (2012) Modelling of the mechanical behaviour of heavily over-consolidated bagasse. *Proceedings of the Australian Society of Sugar Cane Technologists* **34**, (electronic format) 6 pp.

Plaza F (2013) Determining the material properties for heavily over-consolidated bagasse through parameter estimation. *Proceedings of the International Society of Sugar Cane Technologists* **28**, (accepted).

Timoshenko SP, Goodier JN (1982) 'Theory of elasticity'. 3rd edn (McGraw-Hill Book Co: Sydney).