Modelling the round-off and the tensile/compressive failure behaviour of plant and vegetable tissues

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Generally, the constitutive relations of cell walls, the cell turgor pressure, cell geometry, and the cell-to-cell mechanical interactions all have a bearing on the macroscopic stress strain properties of the whole tissue [1-3]. The challenge is, therefore, to develop rheological theories specially for the cellular structure, so that the applied external stress or strain can be related to the internal stress or strain that arise in the cell walls of the individual cells. Experimental results show that the stiffness of plant and vegetable tissues increases strongly with the cell turgor pressure [1, 3]. Assuming that the cell wall material is homogeneous, isotropic and linear elastic, Nilson et al [1] analysed the small deformations of a lattice of identical sphere cells; Pitt [4] and McLaughlin and Pitt [5] qualitatively modelled the cellular structure as a two-dimensional array of hexagons or cylinders; Pitt and Davis [6] modelled the cell wall as a spherical shell by finite element analysis. Using idealised cell structures and experimentally measured cell wall constitutive laws [3, 7,8,9], Pitt et al modelled the compression of plant and vegetable tissues. In reality, the cell walls of plant and vegetable tissues are polymeric composite materials [10], consisting of relative amorphous matrix and a highly structured network of microfibrils embedded in the cell wall matrix [11, 12]. Consequently, the cell wall properties are different in different directions [11, 13]. Taking a lattice of identical and fluid-filled three-dimensional hexagonal cells as the structural model, and using large elasticity theory, Zhu and Melrose [14, 15] introduced three microfibrils stiffening factors in the three principle directions of the cell walls and derived the effective compressive stress-strain relations for the tissue. However, according to our knowledge, all the existing models are mainly focused on modelling the effective properties of the tissues, and none of them can well demonstrate all the main failure mechanisms for a plant or vegetable tissue when it is under an increasing turgor pressure, or under an external compressive/tensile stress.

In this work, plant and vegetable tissues are treated as a lattice of identical 3D hexagonal cells, which are turgored and glued by a layer of the middle lamella pectin, as shown in Fig. 1a. The primary cell walls are treated as an anisotropic rubber-like material and the layer of the middle lamella pectin is treated as a set of one-dimensional springs made of a rubber-like material, as shown in Fig. 1b. Based upon the above mechanical model (Fig. 1b), the following works have been done: a) The cell round-off behaviour is modelled by looking at the deformed cell structure upon the continuously increasing turgor pressure (Fig. 2a), the possible resulting consequence of the cell round-off is cell separation (debonding) or cell wall fracture; b) For a given initial turgor pressure p_{ci}, the mechanical response of the cells to the applied tensile/compressive stress has been simulated (as shown in Fig. 2b). During the tensile/compressive deformation process of the tissue, the turgor pressure in the cells increases while the cell volume remains the same (we assume that the time scale is small and no fluid diffusion takes place during the deformation); c) All the possible failure mechanisms have been analysed, and the effects of the initial turgor pressure on the results a) and b) are discussed.

References

[1] Nilsson, S B, Hertz, C H and Falk, S: **Physiol. Plant. 11**: 818-837, 1958.

[2] Murase, H, Merva, G E and Segerlind, L J: **Trans. ASAE, 23**: 794-796, 1980.

[3] Lin, T T and Pitt, R E : **J. Texture Study. 17**: 291-313, 1986.

[4] Pitt, R E : **Trans. ASAE 25**: 1776-1784, 1982.

[5] McLaughlin, N and Pitt, R E: **Trans. ASAE 27**: 311-320, 1984.

[6] Pitt, R E and Davis, D C: **Trans. ASAE 27**: 1976-1983, 1984.

[7] Gates, R S, Pitt, R E, Ruina, A and Cooke, J R: **Biorheology 23**: 453-466, 1986.

[8] Gao, Q, Pitt, R E and Bartsch, J A: **J. Rheol. 33**: 233-256, 1989.

[9] Gao, Q and Pitt R E: **Trans. ASAE 34**: 232-238, 1991.

[10] Cleland, R: **Ann. Rev. Plant Phys., 22**: 197-222, 1971.

[11] Hettiaratchi, D R P and O'Callaghan, J R: **J. Theor. Biol. 74**: 235-257, 1978.

[12] Wu, H, Spence, R D, Sharpe, J H and Goeschl, J D: **Plant Cell Environ. 8**: 563-570, 1985.

[13] Khan, A A and Vincent, J F V: **J. Texture Stud. 24**: 423-435, 1993.

[14] Zhu, H X and Melrose, J R: **J. Theor. Biol. 221**: 89-101, 2003.

[15] Zhu, H X and Melrose, J R: ***J. Mater. Sci.***, **38**: 2489-2498, 2003.

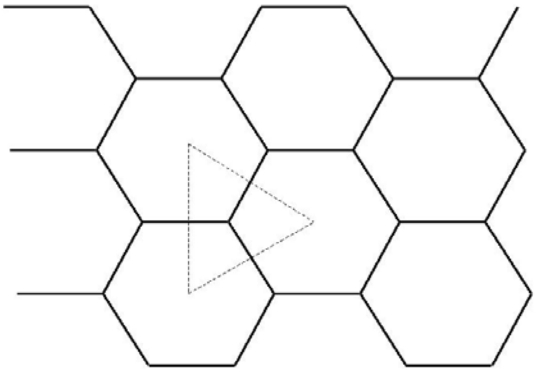

Fig. 1a   Plant and vegetable tissue consists of a lattice of identical 3D hexagonal cells.

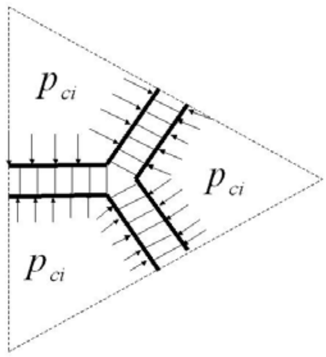

Fig. 1b   The lattice of the initially turgored cells are glued by a layer of middle lamella pectin which are treated as a set of one-dimensional springs.

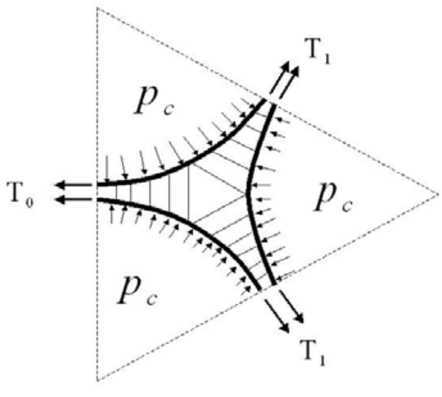

Fig. 2a The cells become round-off under an increasing turgor pressure, with possible resulting consequences: cell separation and cell wall fracture [14, 15].

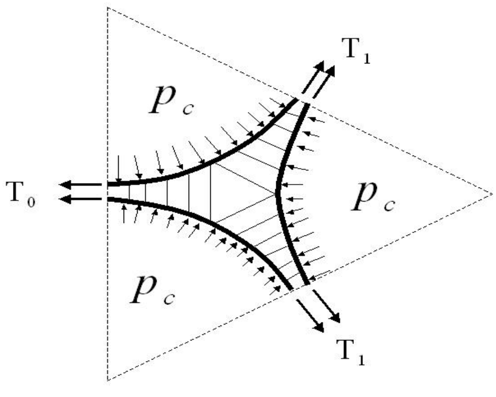

Fig. 2b For a given initial turgor pressure p_{ci}, the cells are deformed under an external tensile/compressive stress, with possible resulting consequences: 1) cell wall fracture and 2) cell deconding initially by separation then by shear [14, 15].