Finite element modeling of external and internal stresses generated in the sunflower’s (*Helianthus annuus* L.) stem after flexure

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ABSTRACT

Stem flexural bending in sunflower seedlings produces important developmental modifications such as stem shortening and early flowering retardation.

In this work, it is hypothesized that for the rapid long distance intra plant signaling transport of the mechanically induced stimulus towards main centers of cellular activity, stem bending generates a significant mechanical stress at vascular level.

A numerical model of the young sunflower stem under static lateral action was studied. Based on its external dimensions and distribution of its constitutive tissues, a 3D finite element model of the stem was built and appropriately meshed. Stresses and strains generated in the surface and inside the stem were calculated.

The FE analysis was made using the Linear Static Stress Analysis modulus of the software ALGOR. Bending due to lateral wind load was simulated by the analogous effect of prescribed displacements with magnitudes adopted from experimental results.

The mechanical behavior of the stem model depends on its global shape and internal structure and is also characterized by the mechanical properties of the stem's constitutive materials as density, Young’s modulus and Poisson’s ratio. Lateral displacements were associated with a significant high bending stress located at the epidermis and vascular tissue.

These observations could help to explain why a mechanical perturbation is highly effective to induce physiological and growth changes at early stages of plant development.

INTRODUCTION

In young sunflower (*Helianthus annuus* L.) plants stem bending or flexing by moderate wind has proved to produce important developmental modifications such as reducing stem elongation [1, 2] and retarding the onset of flowering [3].

These developmental changes observed after flexure can be mainly attributed to thigmomorphogenesis, a growth phenomenon in plants, induced by mechanical perturbation [4]. The mechanostimulus signal transduction pathway leading to thigmomorphogenesis is not yet well defined and the exact mechanism of the thigmoresponse is unknown. Moreover it has still not been properly determined whether the growth response is restricted to the stimulated areas (local) or whether the whole plant (global) is affected [5, 6].

To globally transduce the thigmo stimulus from the site of perception to distant growth centers where active cell reproduction and expansion is taking place, an efficient transport system, other than cell to cell communication pathways via plasmodesmata, has to be present [4]. In this sense the phloem and xylem long-distance translocation system could play an important role as a conduit for the delivery of signaling molecules [7]. It could then be appropriate to assume that the vascular system, particularly the phloem sieve elements (SE), with a velocity of movement of materials ranging from
0.30 to 150 cm/h [8], could be the best route for the signals to be mobilized. If the mechanical stresses generated by shoot bending are located near the vascular strands, it could contribute even more to the mechanostimulus transport efficiency.

In the present work it is hypothesized that stem bending induces to a significant internal mechanical stress at vascular level. For validating the hypothesis, an analysis of young sunflower stems under simulated bending was performed by means of the finite element method (FEM), a well known numerical procedure used for both static and dynamic structural analyses. FEM is the most commonly applied engineering analysis tool for solving problems of continuum mechanics. In the last years, enormous advances have been made in the application of the FEM to solve biological problems [9, 10] unapproachable by other methods because of complexities associated with geometry, material heterogeneous properties, etc. As a result of this biomechanical approach, the superficial and internal stresses and strains were located and calculated. Through this study, the influence of the constitutive material properties and internal structure on the stresses generated in the surface and vascular tissues of the stem were taken into account.

DESCRIPTION OF THE PHYSICAL MODEL

Anatomy

The complex structure of the sunflower stem requires a detailed location of the main tissues within the hypocotyl and epicotyl [11] (Fig. 1c) The relative volumes of its constitutive tissues were defined from properly stained transverse serial sections taken from 23-days old stems of glasshouse grown sunflower plants. As observed from the histological analysis the anatomy of the stem was considered to be composed of twenty two strands of vascular tissue in the hypocotyl (0 to 4.0 cm; Fig. 1a,c) and eleven in the epicotyl (4.0 to 10.0 cm; Fig. 1b-c).

Biomechanical properties

With reference to the constitutive properties of biological materials, a significant amount of information is available in the literature. The Young's modulus of epidermis and parenchyma as well as its Poisson ratios were taken from [12, 13, 14]. The Young's modulus of the fiber strands was from [15]. Tissue density was estimated from the weight of stem segments of known dimensions and the relative proportions for each tissue estimated from the surface areas of each constitutive tissue, measured from hypocotyl's transverse cuts.

DESCRIPTION OF THE NUMERICAL MODEL

FE Model

Based on the distribution of tissues (Fig. 1a-b) and its real external dimensions and global geometry (Fig. 1c), a 3-D model of the stem was generated and properly meshed using the brick structural element [16]. Six and eight-nodal solid elements were used giving the model a final configuration of 30891 elements with 28433 nodes (Fig. 1c).

Constitutive materials

Even though it is known that the strengthening tissues in stems are highly anisotropic [17], for simplification purposes the model assumes isotropy and was considered to be composed by seven tissues incorporated as six independent element groups of isotropic material (Fig. 1a-b) characterized by the following properties: Young's modulus (E), Poisson's coefficient (ν) and density (δ). The assumed values for each group are: (Ep+CPa): E(MN)= 8.5; ν= 0.25; δ (Kg/m³)= 960; OuMP: E= 5.3; ν= 0.25; δ= 880; FS: E= 12.5; ν= 0.25; δ= 1,000; InMP: E= 4.0; ν= 0.25; δ= 600; Phl: E= 6.5; ν= 0.25; δ= 960; Xyl: E= 8.5; ν= 0.25; δ= 1,000; see Fig. 1a-b for tissue location and notation).
FE Analysis

The FEM was used to analyze the mechanical behavior of a stem model using the Linear Static Stress Analysis modulus of ALGOR [16] (vers. 17, Algor Inc., Pittsburgh, PA).

A model based on beam theory is often used to compute stresses in slender plant stems [17]. Thus, from a structural point of view, the stem was considered as a tapered beam model clamped at the bottom and free at the apical end. The external action due to the wind was replaced by an equivalent displacement to perform the bending analysis. The base of the model was fixed and a prescribed displacement (PD) of 0.05m (Fig. 1c) was applied at the opposite free apical end. It was assumed to be enough to induce stem’s bending in field grown 23-days old sunflower plants exposed to a wind speed of 5 m.s\(^{-1}\) [3] and to keep the analysis in the linear domain. Results of stresses and displacements at different locations were registered for the deformed stem.

RESULTS

Numerical results of stresses

One of the principal topics in mechanics of solids is the analysis of the stresses and deformations within a body subjected to a prescribed system of forces. In our case, the external action was applied in terms of prescribed displacements (instead of applying a force).
It is well known that the complete description of the stress state at a point requires specification of the stress on three mutually perpendicular planes passing through the point. Von Mises stress (VMS) is frequently used to characterize the stress state (the normal and shear stresses) at a particular point, giving an appreciation of the overall magnitude of the stress tensor. More precisely, VMS is a scalar function of the components of the stress tensor that is proportional to the strain energy density associated with a change in shape (with a zero volume change) at a material point.

Fig. 2. Distribution of axial stress ($\sigma_x$; A-B). Maximum stress ($\sigma_m$; C-D) and von Mises stress (VMS; E-F) at the surface and inside the model at sections denoted as "S".
In 3-D, the von Mises stress can be expressed in terms of a global coordinate system (Eq. 1), as:

\[
\sigma_v = \frac{1}{\sqrt{2}} \sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)}
\]  

Or, in terms of the principal stresses \(\sigma_1, \sigma_2, \sigma_3\) (Eq. 2):

\[
\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}
\]

Principal stress is the maximum stress due to all the stresses combined together. In this case the principal stresses (\(\sigma_1, \sigma_2, \sigma_3\)) are defined in the principal directions (1,2,3).

It must be remarked that VMS is only physically meaningful for isotropic materials and should not be used in the case of the anisotropic materials involved in the stem structure. Nevertheless, for the purpose of the present study the use of VMS is acceptable based on the following considerations.

Figure 2 shows a comparison of the distribution of stresses (longitudinal, maximum principal and Von Mises) over the stem’s surface. In Fig. 2 the distribution of stresses inside the stem are also shown at a transversal section located in the critical area immediately above the cotyledonary node (over the tapered region of the stem). It can be observed that the three referred stresses reached similar values and all were situated at the proximity of the vascular tissue.

It can also be observed that the vascular fiber strands (FS) experience the highest stresses in the longitudinal (x) direction, followed by the external ‘ring’ of epidermis plus cortex parenchyma (Fig. 1 a-b; Fig. 2). This is a consequence of the high values of the Young’s modulus of the respective constitutive materials being stiffer, generates higher stresses (FS: E=12.5MN; Xyl: E=8.5MN; Ep+Cpar: E=8.5MN). This observation is also valid for VMS and the maximum principal stress (Fig. 2).

Being \(\sigma_x\) the most significant stress (tension and compression along the stem) and notably higher than \(\sigma_y\) and \(\sigma_z\) allows us to define that both can be neglected in the calculus of VMS. This simplification results in an acceptable coincidence between Von Misses and maximal stress criteria (uniaxial).

From a structural point of view, it is interesting to denote that the stress distribution at section S in Fig. 2 recalls the behavior of a typical tied circular column. Such type of column has a longitudinal reinforcement provided by straight steel bars and a transversal reinforcement given by rings that surround the longitudinal bars. There is an analogy between the fiber strands and the epidermis with longitudinal bars and the “tie” respectively (Fig. 1).

Fig. 3 shows the VMS patterns attained for bending at two critical sections of the stem, proximate to the cotyledonary node. Section S is located above and S’ below the cotyledonary node. It can be seen that the localization and distribution of maximum VMS values are always significantly higher near the vascular tissue (Fig. 3).

Displacements of different magnitude to simulate bending in time (not presented here) show that high stress tensions locates near the vascular strands were displaced from bottom to top. Moreover, the sequential results of the simulation after the completion of maximum bending, show that stresses are mainly located close to the cotyledonary node (Fig. 2; Fig. 1C).
Fig 3. Calculated stresses at the end of the bending simulation in two critical sections of the stem model (S and S'). A prescribed displacement was oriented as in PD. Note that higher external and internal stress magnitudes are distributed towards the stem base. Also note that the higher stress values (von Mises: N.m$^{-2}$) correspond to the sites where a significant proportion of the vascular tissue is located. VS: Vascular strands. Scale bar in m.

BIOLOGICAL IMPLICATIONS

The proximity of stressed cells to the phloem and xylem elements support the hypothesis that mechanical stimulus not only can act at surface level but can be also acting at vascular tissue level boosting the transport transfer of the induced mechanical stimulus.

There is experimental evidence that higher plants have evolved a mechanism that allows the selective translocation of long-distance signaling molecules by the phloem, for delivery to distant organs of the plant [18].

The phloem translocation stream could then serve as a conduit for the long-distance delivery of proteins and ribonucleoprotein complexes that could act in signal transduction cascades involved in the integration of developmental and physiological processes occurring within distantly located organs [4]. That could be the way in which higher plants integrate developmental and physiological processes at the whole-plant level.

CONCLUSIONS

The numerical model described in this paper, is a theoretical and simplified representation of a young sunflower stem, its constitutive tissues and their biomechanical properties. The obtained results confirm the capability of the model to predict stress distribution patterns inside the structure, taking into account the combined effects of geometry, materials and loading. The FE model is based on a realistic (though approximate) geometry and includes various hard and soft tissue components. Since the aim of this study is to obtain qualitative results, the computed stresses can be considered as representative of a possible and real loading state of the stem. The
present model can help to understand the influence of the mechanical stresses on the growth response.

ACKNOWLEDGEMENTS

This work was funded by grants to L.F.H. of the Agencia Nacional de Promoción Científica y Tecnológica and the Argentine Sunflower Association (ANPCyT-ASAGIR, PICTOS No. 13151), the Secretaria Gral. de Ciencia Tecnología (SeGCyT-UNS) and the Comisión de Investigaciones Científicas (CIC-PBA, LaPlata), Argentina.

REFERENCES