ORIGINAL ARTICLE

Numerical Model for Sugarcane Base Cutting

Modelo numérico del corte base de la caña de azúcar

CU-ID: 2177/v31n2e02

Rigoberto Antonio Pérez-Reyes[I*], Lázaro Antonio Daquinta-Gradaille[I], Jorge Douglas Bonilla-Rocha[I], Carlos Alexander Recarey-Morfa[II], Anibal Sánchez-Numa[I], Julio Eustaquio Gómez-Bravo[I]

[I]Universidad de Ciego de Ávila, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba.
[II]Universidad Central de Las Villas, Facultad de Construcciones, Santa Clara, Villa Clara, Cuba.

ABSTRACT: In the present work, a numerical model is developed for sugarcane base cutting from experimental data obtained in five varieties of cane evaluated in the Physics and Resistance of Materials Laboratories of Ciego de Ávila University. The performance of the BONEM and BUSSOLA base-cutter blade was analyzed in relation to process parameters such as stresses, cutting force and cutting moment. It was shown that BUSSOLA cutter blade had a better performance than BONEM for each of the varieties tested. In the analysis of a model with average magnitudes of the physical-mechanical properties of the stems of the varieties examined, the behavior graphs of the cutting forces over time and the Force - Displacement graphs for both segments were obtained. The main results show that there are no representative differences in relation to the magnitude of the stresses generated in the stems of each of the sugarcane varieties when they are cut with the different cutter blades. In addition, it was shown that the magnitudes of cutting force and cutting moment generated with the use of BONEM cutter-blade are significantly higher than those generated with BUSSOLA cutter-blade.

Keywords: Finite element method, sugarcane mechanized harvest, base-cutter blades.

RESUMEN: En el presente trabajo se desarrolla un modelo numérico para el corte base de la caña de azúcar a partir de datos experimentales obtenidos en cinco variedades de caña evaluadas en los laboratorios de Física y Resistencia de Materiales de la Universidad de Ciego de Ávila. Se analizó el desempeño de los segmentos de corte base BONEM y BUSSOLA con relación a parámetros del proceso como las tensiones, la fuerza de corte y el momento de corte. Se demostró que los segmentos de corte BUSSOLA poseen un mejor desempeño que los segmentos BONEM para cada una de las variedades ensayadas. En el análisis de un modelo con magnitudes promedios de las propiedades físico-mecánicas de los tallos de las variedades examinadas se obtuvieron los gráficos del comportamiento de las fuerzas cortantes en el tiempo y los gráficos de Fuerza - Desplazamiento para ambos segmentos. Los principales resultados muestran que no existen diferencias representativas con relación a la magnitud de las tensiones generadas en los tallos de cada una de las variedades de caña de azúcar cuando se cortan estas con los diferentes segmentos de corte y las magnitudes de fuerza de corte y momento de corte generadas con el empleo de los segmentos BONEM son significativamente superiores a las que se generan con los segmentos BUSSOLA

***Palabras clave*:** Método de elemento finito, cosecha mecanizada de la caña de azúcar, segmentos de corte base.

*Author for correspondence: Rigoberto Antonio Pérez-Reyes, e-mail: rigobertopr@unica.cu
Received: 06/01/2021
Accepted: 14/03/2022

INTRODUCTION

The base cutting is one of the main functions of the sugarcane harvester, it is the most delicate operation for the incorporation of soil and stools, the destruction of crop and losses of cane left in the field due to the excessive height of the stump. The quantity and quality of the cane that goes to the mill largely depends on its efficiency. Anything that is contaminating material (mainly soil and parts of the plant) that enters the system, reduces the milling capacity and increases the losses of sucrose in the sugar production stages (Abadia, 2018; Valeiro y Biaggi, 2019).

The current harvesters use a base cutting mechanism with a rotating disc that cuts without support and by impact of the sugarcane stalks. Generally it consists of two rotating discs with opposite rotation that perform the cut with replaceable cutter segments (blades) in each disc installed on its periphery, acting with 60% of its contact area cutting the cane against the ground (Ma *et al.*, 2014). To complete the cut, the force exerted at the peripheries of the cutting point must be greater than the total resistance force. Most of the relevant studies by Otegui *et al.* (1995); Kroes (1997); Mello & Harris (2003) and Toledo *et al.* (2013), investigate the base cutting of a single stem, considering that the study investigates the quality of the base cutting of a whole seedling (multi-stem stool).

Handong *et al.* (2011) perform the simulation of the sugarcane cutting process based on ANSYS / LS-DYNA. Different finite element models are built with different tool angles and cutting speeds. The result of the simulation reveals that the effect of the cutting speed on the energy consumption of the cutting force and the maximum stress of the tool is significant, as it is the effect of different angles of the tool on the cutting force. Hu *et al.* (2016) simulate the movement of the sugarcane base cutter using a finite element model (FEM) in order to obtain the nomograms of the tension in the cane, the displacement of the base cutter and the cutting force curve. Geometric and kinematic parameters of the base cutter are evaluated, such as the angle of the cutting edge of the blades, the angle of inclination and the speed of rotation of the cutting disc, as well as the speed of advance of the machine. The value of this research is that it offers the possibility of improving the cutting quality of the base cutter and reducing the magnitude of the cutting force.

Rezende (2020) executes a simulation of the basal cutting of a sugarcane stem considering the anisotropic and heterogeneous material (bark and nucleus). In the study, the mechanical properties of the RB966928 cane are used, as it is the most common variety in the southeast of Brazil. As fundamental results it was obtained that the maximum stresses obtained in the cane cut were 24.11 MPa in the bark and 10.29 MPa in the core. According to the author, these magnitudes differ by 30% from the average values found in the published literature, and the shear angle was the factor that most influenced the magnitude of the stresses.

Qiu *et al.* (2021) use finite element numerical simulations and an experimental design to investigate the influences of internal and external factors on the quality of the cut. The numerical model is validated through experimental cut-off tests and based on a theoretical analysis. They conclude that the cutting bevel angle plays a significant role in affecting the cutting force, while the feed rate of the machine (within the range 0,4 to 0,6 m /s) and the rotational speed (within range 650 to 750 r /min) have no appreciable influence on the cutting force. This study provides basic information for the design of a base cutter for sugarcane harvesting.

The objective of this research is to develop a numerical model for the base cutting of sugarcane from experimental data obtained in five varieties of cane representative of the province of Ciego de Ávila for the analysis of the performance of the base-cutter blade BONEM and BUSSOLA in relation to process parameters such as stresses, cutting force and cutting moment. The simulation environment validation is carried out from a cutting resistance test and the base cutting of the sugarcane is studied, consisting on the simulation of the working conditions with the two types of blades selected for the study, with the purpose of evaluating the response of the model in terms of the fundamental operating parameters that characterize the base cutting process found in the literature and to predict the performance of the two cutter blade under certain operating conditions.

METHODS

To study the performance of the base-cutter blade, numerical simulation was used, using experimental modeling as a calibration tool based on data obtained in real tests of the base cutting process. The computer program Abaqus (2014) from the company Hibbit, Karlsson & Sorencen, Inc., a valuable general-purpose program based on the Finite Element Method (FEM), was used. Specifically, the ABAQUS / Explicit version is chosen, designed for dynamic problems. Explicit dynamics is a mathematical technique to integrate the equations of motion through time, these equations of dynamic equilibrium are written for convenience with the inertial forces isolated from the other forces and are completely general (Abaqus 2014). Equation (1) describes this relationship.

$$M\ddot{u} = P - I \quad (1)$$

where: M is the concentrated mass, $\ddot{u}$ the nodal acceleration, P is the external charge vector and I is the internal charge vector.

The explicit dynamics integration method combines the explicit dynamic integration rule with elements that use a concentrated mass matrix. This matrix *M* allows the program to calculate the nodal accelerations easily at any given moment of time t, using the following expression:

$$\ddot{u}_{(t)} = \left| M^{-1} \cdot (P - I) \right|_{(t)} \quad (2)$$

The decisive factor when choosing ABAQUS / Explicit is usually the fluidity of the solution when there are significant discontinuities in it, such as: possible sources of discontinuity; impact; degradation or failure of the material. It has been designed to solve high-speed and highly discontinuous dynamic problems efficiently and has a very robust contact algorithm that does not add additional degrees of freedom to the model Abaqus (2014).

The decisive factor when choosing ABAQUS / Explicit is usually the fluidity of the solution when there are significant discontinuities in it, such as: possible sources of discontinuity, impact, degradation or failure of the material. It has been designed to solve high-speed and highly discontinuous dynamic problems efficiently and has a very robust contact algorithm that does not sum additional degrees of freedom to the model Abaqus (2014).

Construction of the model to validate the simulation environment. A numerical model was built that reproduces the experimental cutting resistance test for the validation of the simulation environment. Numerical reproduction was carried out in the internode area of variety C1051-73 with an average diameter of 27,62 mm and an average energy absorbed in the test of 28,5 J during cutting with the BONEM blade (Figure 1). Several numerical-experimental runs were carried out on the same conditions established in the study until the convergence of the mesh was achieved, analyzing the magnitudes of internal energy reached during the experimentation.

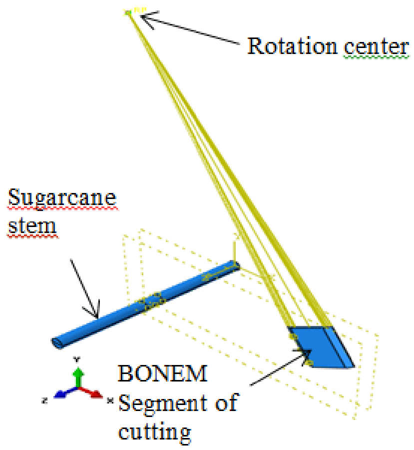


FIGURE 1. Numerical reproduction of the cutting resistance test in the internode area of variety C1051-73.

In Figure 2, it is observed that to guarantee the reliability of the results it is necessary to consider a mesh of 29 289 elements, with 3 564 elements in the blade and 25 725 elements in the stem. The results of the numerical run are reflected in Table 1, where it is observed that the magnitude of the error obtained between the experimental test and the numerical model is less than 5%, which means that the model is capable of adequately reproducing the real conditions of experimentation.

Modeling the base cutting of the sugar cane stems. The study of convergence of the mesh for the

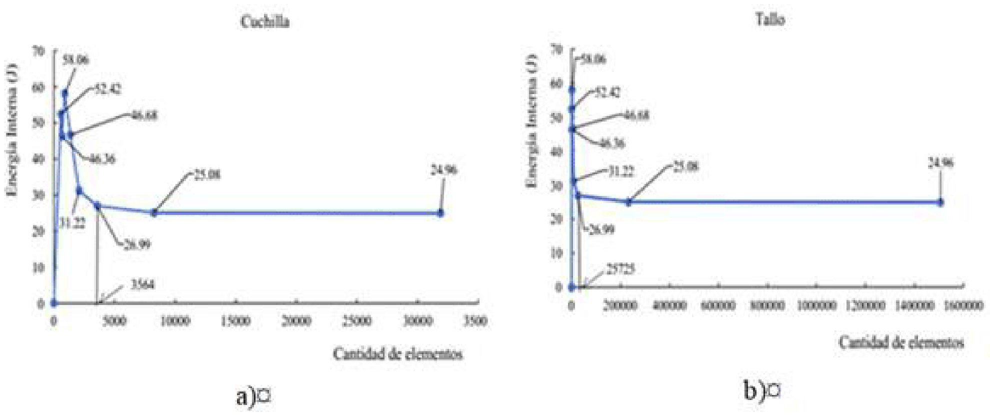


FIGURE 2. Mesh convergence study for the validation of the numerical model of the cutting energy test: a) For the blade; b) For the stem.

TABLE 1. Validation results of the cutting energy test

Variety of sugarcane	Experimental test	Numerical model	Error (%)
	Cutting energy (J)	Cutting energy (J)	
C120-78	28,50	27,06	3,53

simulation of the numerical models of the base cutting of sugarcane can be seen in Figure 3. In that figure, it is observed that, to guarantee the reliability of the results, it is necessary to consider a mesh of 42 350 elements, with 28 350 elements on the blade and 14 000 elements on the stem.

To model the behavior of the material of the base cutter blade (steel), the works of Domínguez *et al.* (2012); Hu *et al.* (2016) and Ma *et al.* (2016) are considered, with the Von Mises break criterion. The results obtained in the work of these researchers show a great correspondence between experimentation and numerical simulation, facts that validate the use of said criterion to model this material. To apply this behavior, the PLASTIC command of the ABAQUS code is used. Various authors have studied the mechanical properties in tension of vegetable fibers like Cortés (2009); Silva *et al.* (2009) and Kestur *et al.* (2012) which are required to implement a numerical model. In the case of sugarcane, as a biological material, it has a complex structure, composed of the bark and the nucleus, which is a non-linear and heterogeneous anisotropic viscoelastic material.

The behavior of viscoelastic materials varies in a large range, these materials represent the unit of elastic behavior, expressed by Hooke's law and viscous fluids, which are expressed by Newton's law. A solution must be found to reproduce two behaviors. To model using the theory of viscoelastic materials, a model for each type of test should be found, which would contradict the objective of determining a behavior capable of simulating different load systems. Consequently, the model of mechanical behavior manifested through the modulus of elasticity should have parameters that give it sufficient flexibility to reproduce the behavior of the experimental curves obtained (Iznaga & Braunbeck, 2011).

However, considering the differences in the physical and mechanical properties of the several varieties of sugarcane and that the axial cutting failure values are low, the numerical model of the sugarcane stem is simplified and considered as an isotropic material, with a bilinear elastic-plastic model with kinematic hardening (Saldaña *et al.*, 2013; Dongdong y Jun, 2016; Hu *et al.*, 2016; Yuan *et al.*, 2017). The kinematic-plastic model is as follows:

$$\sigma_y = \left|1 + \left(\frac{\dot{\varepsilon}}{C_p}\right)^{\frac{1}{p}}\right|\left(\sigma_0 + \beta\varepsilon_{eff}^{p}\frac{E_t E}{E - E_t}\right) \quad (3)$$

where: σy - Yield limit; ε - Speed of deformation; C and P - They are the symbols of Cowper and Simonds; σ_0 - Elastic limit; $\beta = 0$ for kinematic hardening and 1 for isotropic hardening; $\varepsilon peff$ - Effective plastic deformation; E - Modulus of elasticity; Et - Tangent modulus.

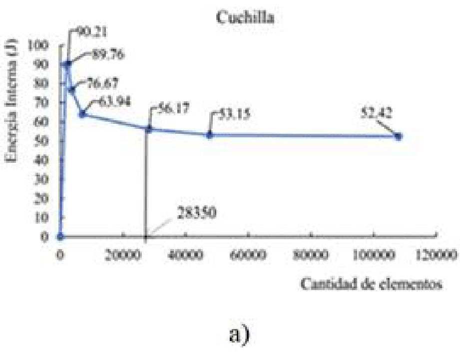
For the model, the hardening effect is neglected due to the speed of deformation, because it is the simplest approximation of an elastic-plastic model and is a more realistic approximation to the material.

Therefore, expression (3) results in: $\sigma_y = \sigma_0$ (4)

The definition of the material properties of the sugarcane and the deformable blade was executed in the PROPERTY-EDIT MATERIAL module, with a material of uniform density and an elastic-plastic behavior with kinematic hardening for the sugarcane and a material of uniform density and an elastic-plastic behavior with isotropic hardening for the blade. The properties of the rigid base cutter and blade are defined in the PROPERTY-SPECIAL-INERTIA-CREATE module for the reference point (rotation center) created in the PART-TOLLS-REFERENT POINT-CREATE module. Table 2 shows the properties of the materials used in the modeling with average physical characteristics and mechanical properties of the five varieties studied, for the analysis of the influence exerted by the geometric and kinematic parameters in the cutting process.

Geometry modeling. It has been decided to adopt the three-dimensional modeling of the specimens (3D), thanks to the benefits in terms of geometric representation provided by ABAQUS / CAE, being consistent with their configuration in the experimental test. The constitutive models developed (single blade and base cutter) are made up of:

- A sugarcane stalk 28 mm in diameter and 500 mm in length with a tool steel BONEM blade that is 270 mm long, 90 mm wide, 6 mm thick and has a cutting-edge angle of 25° (Figure 4a).



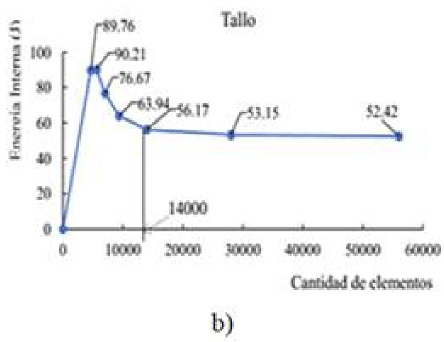


FIGURE 3. Mesh convergence study for the b

TABLE 2. Properties of the materials used in the numerical modeling with average physical characteristics and mechanical propertie

Property	Sugarcane	Steal of the cutting segments	Steal of the base-cutter disk
Specific mass (g/cm^3)	ρ = 1,13	ρ = 7,85	ρ = 7,85
Module of elasticity (MPa)	E = 17,357	E = 2,1x10^5	E = 2x10^5
Poisson coeficient	υ = 0,34	υ = 0,28	υ = 0,3
Friction coeficient	0.588		
Fluency tension (MPa)	σ_y = 37	σ_y = 340	σ_y = 120

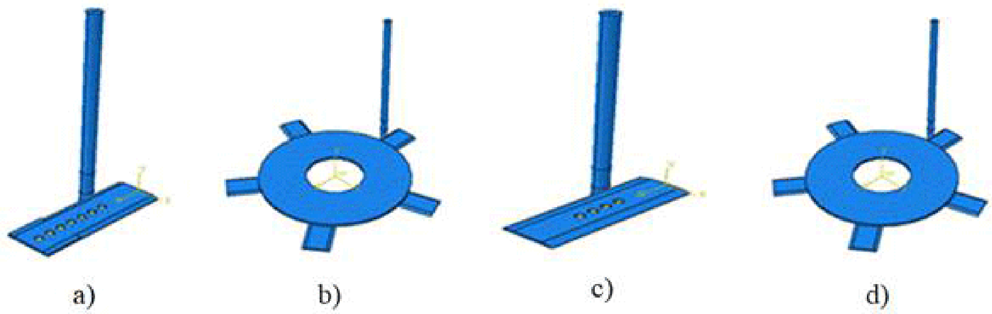


FIGURE 4. Geometry applied to the parts after the assembly process: a) and b) with a BONEM blade; c) and d) with BUSSOLA blade.

TABLE 3. Contact properties

Sliding Formulation	(*Finite Sliding*)
Discretization Method	(*Surface-to-Surface*)
Tangencial Contact Formulation	(*Penalty)*
Normal Contact Formulation	(*Hard contact*)

- A sugarcane stalk 28 mm in diameter and 500 mm in length with a tool steel BUSSOLA blade that is 270 mm in length, 90 mm in width, 6 mm in thickness and a 15° cutting edge angle (Figure 4c).
- A hollow circular base-cutter disk of structural steel and 21 inches (533,4 mm) outside diameter, 8 inches (203,2 mm) inside diameter, and 8 mm thick; five BONEM blades attached to it, evenly distributed with an angle of 72° between them, and sugarcane stalks 28 mm in diameter and 500 mm long (Figure 4b).
- A hollow circular base-cutter disk of structural steel and 21 inches (533,4 mm) outside diameter, 8 inches (203,2 mm) inside diameter, and 8 mm thick; five BUSSOLA blades attached to it, evenly distributed with an angle of 72° between them, and sugarcane stalks 28 mm in diameter and 500 mm long (Figure 4d).

For the development of the numerical models, the contact geometry between the interacting bodies (cane stem and base cutter blade) was considered, which in this case, conforms to one of the geometries widely studied by Contact Mechanics: Cylinder-Flat (CF). For the simulation of the contact between the bodies in ABAQUS, it was necessary to define the *master* and *slave* surfaces, which are only delimited in the region where the contact is actually going to occur, so that unnecessary computational time is required. In this case, the cutter-blade edge is established as the master surface and the contact zone of the stem as the slave surface, specifying the properties of the contact as shown in Table 3. The method of surface-to-surface discretization is selected (*Surface-to-Surface*), because it presents better results than the *Node-to-Surface* method, which can produce maximum errors of up to 31% (Abaqus, 2014). For the formulation of the tangential contact the penalty method (*Penalty*) is used, since the augmented Lagrange method is not available in ABAQUS / Explicit. For the formulation of normal contact, the rigid contact method (*Hard contact*) is used, with entry into force of the restrictions that allow separation after contact. (Cruzado *et al.*, 2013).

Modeling of the boundary conditions of bodies and loads.

The stem of the sugarcane: this element is considered embedded in its base, with restriction of movement in all directions (Figure 5a). A thrust load of a magnitude equal to 2 kN (Figure 5c) is applied to it in the longitudinal direction (Z), simulating the effect of the deflector roll (Figure 5b).

Rigid elements: both in the single blade model and in the base-cutter model, a reference point (rotation center) is created to which the values of the inertia of the moving bodies are assigned. All displacements are restricted to the single blade, except for rotation in the vertical axis (Y), around which a rotational movement of magnitudes equal to 65 rad /s is assigned in each case. It was similarly done for the base cutter, with the difference that, in addition to the rotation in the vertical axis (Y), the linear movement in the longitudinal direction (Z) is also left free, to simulate the translation of the machine during the cut with a value of 1.39 m/s.

Deformable elements: in these, a reference point (rotation center) is also created, but with the aim of linking it with the elements of the model (blade and base cutter) through a coupling and assigning the restrictions and movements.

Finite element type selection and mesh density calibration. ABAQUS has three different typologies in its library of solid elements (3D): C3D8 6-sided binoculars, C3D6 5-sided binoculars (wedges) and C3D4 tetrahedral (pyramid with a triangular base). For the selection of the type of finite element, the geometry of the bodies to be modeled and the recommendations of authors such as Dongdong & Jun (2016); Hu *et al.* 2016 and Ma *et al.* (2016) were considered.

In the contact zone (Figure 6), where the most critical values of the stress, strain and pressure distribution fields are verified, a more detailed refinement of the mesh is carried out. According to this principle, the elements in contact are divided into three parts: contact zone, transition zone and non-contact area. For the sugarcane stem, with a cylindrical geometry throughout its length, the C3D8R 6-sided prismatic element was selected, with 8 nodes and reduced integration, with a mesh size that becomes denser towards the contact zone, where reaches a size of 2 mm. For the blades and the base cutter, the C3D6 6-node linear triangular prismatic element is chosen. In the blades, the mesh becomes denser towards the edge area (contact area), where it reaches a magnitude of 4 mm. In the case of the disc (non-contact area) the mesh reaches a value of 30 mm.

Selection of the fault model. Since the material in cut is subject to impacts, it is greatly affected by large deformations and high rates of deformation. The shear failure model is designed for high strain rate deformation of many materials and uses equivalent plastic deformation as a measure of failure. It offers two options for what happens in the event of failure,

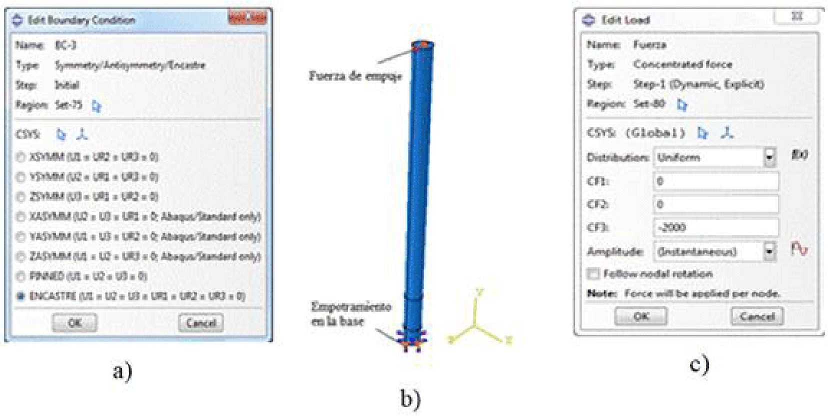


FIGURE 5. Definition of stem boundary conditions.

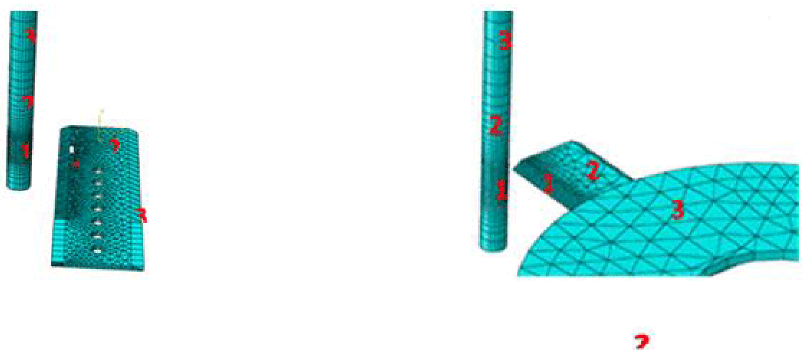


FIGURE 6. Zone discretization of the bodies that involve contact. (1-Contact zone; 2- Transition zone; 3- Non-contact area).

including removing elements from the mesh, and it can be used in conjunction with Von Mises plasticity models to define the failure for the material cutting. It is based on the value of the equivalent plastic deformation at the integration points of the element and assumes that the failure occurs when the damage parameter exceeds the value 1 Abaqus (2014). The damage parameter, ω, is defined as:

$$\omega = \frac{\varepsilon_0^{-pl} + \sum \Delta\varepsilon^{-pl}}{\varepsilon_f^{-pl}} \quad (5)$$

ε_0^{-pl} _ is any initial value of the equivalent plastic deformation.

$\Delta\varepsilon^{-pl}$ _ is an increase in equivalent plastic deformation.

$\Delta\varepsilon^{-pl}$ - is an increase in equivalent plastic deformation.

ε_f^{-pl} - is the deformation at the moment of failure and the sum is made over all the increments in the analysis.

RESULTS AND DISCUSSION

In Figure 7a, the behavior of the stresses in the different cutter blades is observed and in Figure 7b, the behavior of the stresses in the stems, for each variety of sugarcane studied during the simulation of the cutting process of a single stem with speed angle of cutting of 65 rad /s and angle of inclination of cutting equal to 0º. In it, it can be seen that the magnitude of the stresses in the BUSSOLA blades are lower than with the BONEM blades, which corroborates the criteria of Valdés *et al.* (2009) on the influence of the edge angle of the cutter-blades on the magnitude of the stresses generated in these tools. It is also observed that there are no representative differences in relation to the magnitude of the stresses generated in the stems of each of the sugarcane varieties when these are cut with the different blades. It is also distinguished that the C90-469 variety achieves the highest stress values, while the C120-78 achieves the lowest magnitudes in this parameter.

Figure 8 represents the behavior of the cutting forces for the stems and the cutting moment in the base cutter of the five varieties of sugarcane studied with the two types of cutter blades, with cutting angular velocity of 65 rad /s and an angle of inclination of the cutting equal to 0º. In it, it is observed that the magnitudes of cutting force and cutting moment generated with the use of the BONEM blades are significantly higher than those generated with the BUSSOLA blades, which confirms the results of authors such as Mello & Harris (2003); Qingting *et al.* (2007); Valdés *et al.* (2009) ; Hu *et al.* (2016); Shen *et al.* (2016) and Qiu *et al.* (2021) that refer the influence of the tool geometry on the magnitude of these parameters. The variety C90-469 has the highest value of the analyzed parameters for both blades.

Figure 9 shows the magnitudes of the tension and reaction force in the stems and the reaction moment in the base cutter of the C90-469 variety for both cutter-blade.

Table 4 shows the results of the comparison of the power magnitudes obtained from the cutting moment of each variety with the results of Pérez *et al.* (2019), who carried out an assessment of the loads in the sugar cane harvester under Cuban conditions and determined that the organs with the highest power consumption are the base cutting discs with 20.4 kW. The power is determined by the expression:

$$Mt = \frac{N}{\omega} \quad (6)$$

where: *Mt* - Torque moment transmitted by the base-cutter shaft or cutting moment (N · m); *N* - Power transmitted by the shaft (W); *ω* - Angular velocity of the shaft (rad /s).

Therefore: $N = Mt.\omega$ (7)

The angular velocity of cutting (ω) for the calculation is 65 rad /s.

The greatest difference between the power obtained in the modeling and the power value reported by Pérez *et al.*(2019) was obtained for the C86-156 variety

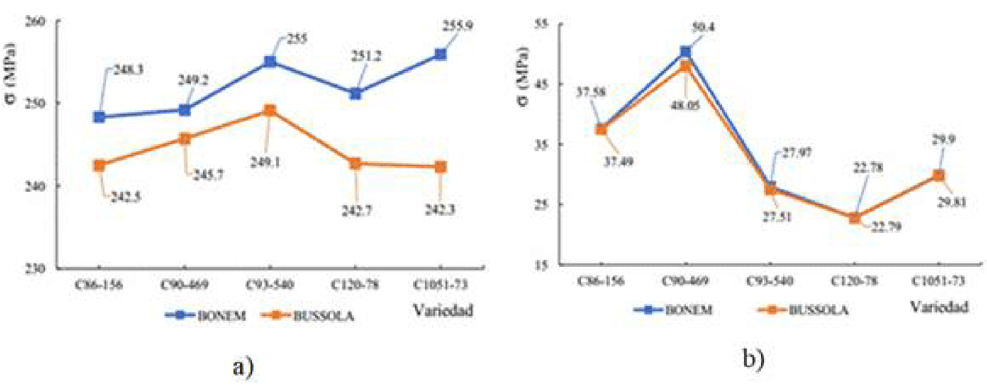


FIGURE 7. Behavior of stresses: a) in the different cutter blades, b) in the stems, for each variety of sugarcane studied at 65 rad/s and angle of inclination of cut equal to 0º.

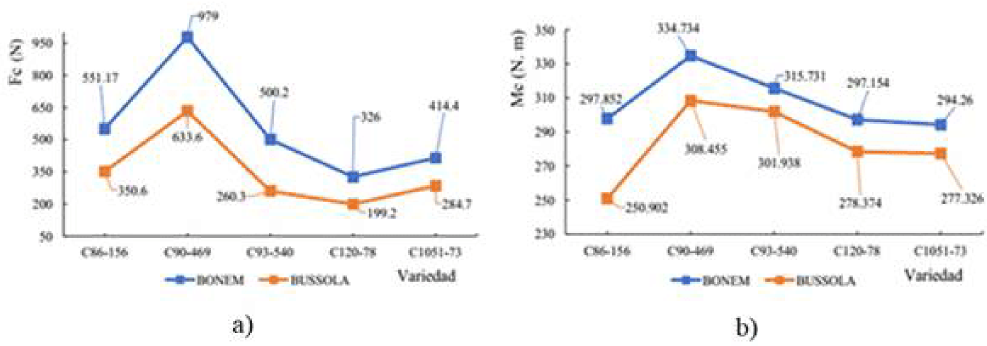


FIGURE 8. Behavior of: a) cutting forces in the stem, b) cutting moment in the base cutter for each variety of sugarcane studied with the different cutter blades at 65 rad/s and angle of inclination of cutting equal to 0º.

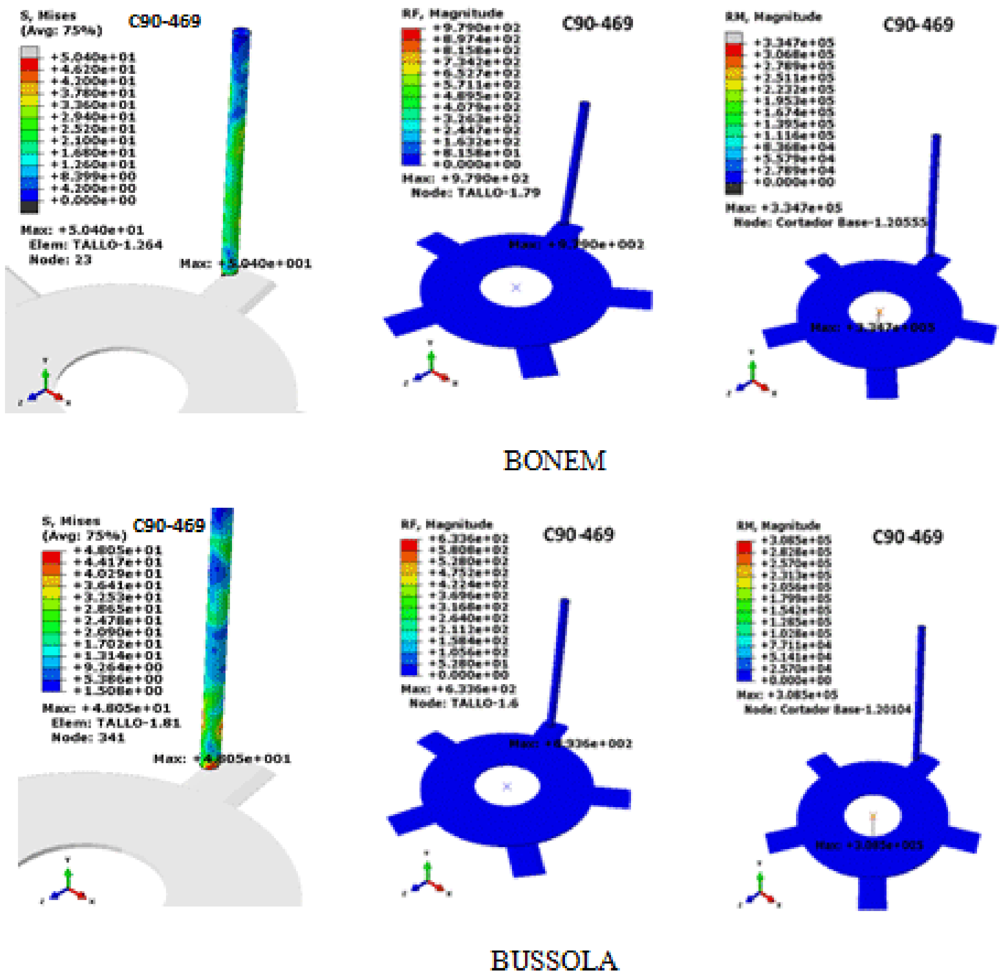


FIGURE 9. Magnitudes of the maximum stresses, reaction forces in the stems and the reaction moment in the base cutter of the C90-469 cane variety.

with the BUSSOLA base-cutter blade, which reached 20,05%, an acceptable difference in the field of numerical studies. In the rest of the varieties, the difference ranges between 0.59% in the C93-540 variety with the BONEM blade and 11.62% in the C1051-73 variety with the BUSSOLA blade.

Figure 10 shows the magnitudes of the stresses in the stem, in the cutter blade and the displacement of the base cutter at the instant of cutting at an angular velocity equal to 65 rad /s and 0º inclination of the cutter disc for the BONEM and BUSSOLA blades, corresponding to the model with average values of the physical-mechanical properties of the stems, where the fundamental difference is seen in the magnitude of the stresses that arise in the cutter blades, which are higher in the BONEM blade that has a greater cutting edge angle.

TABLE 4. Results of the comparison of the power magnitudes obtained from the cutting moment of each variety

Sugarcane variety	Cutting moment (N m)	Power obtained (kW)	Mean power (kW)	Difference (%)
		BONEM		
C86-156	297,52	19.34		5,19
C90-469	334,734	21,76		6.67
C93-540	315.731	20,52	20,4	0,59
C120-78	297,154	19,32		5.29
C1051-73	294,26	19,13		6,23
		BUSSOLA		
C86-156	250,902	16,31		20,05
C90-469	308,455	20,05		1,72
C93-540	301,938	19,63	20,4	3,77
C120-78	278,374	18,09		11,32
C1051-73	277,326	18,03		11,62

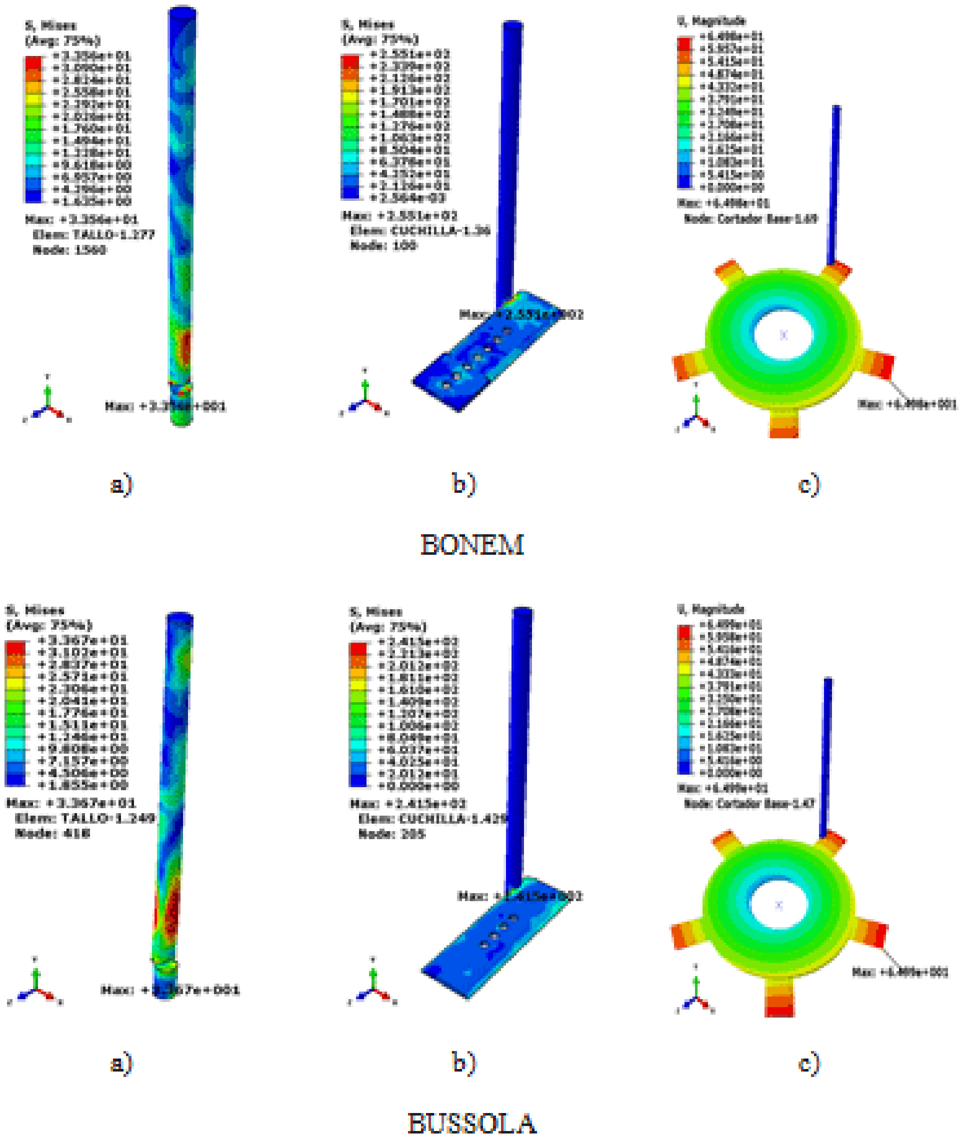


FIGURE 10. Magnitudes at the instant of cutting for models with average values of the physical-mechanical properties of the stems: a) stresses in the stem (MPa), b) stresses in the base-cutter blade (MPa), c) base cutter displacement (mm).

Figures 11, 12, 13 and 14 show the stress nomograms in the stems and the base-cutter blades during the cutting of a stem with average magnitudes of the physical-mechanical properties of the varieties studied, where it is observed as the tension in the sugarcane during the cutting process is small and its maximum equivalent stress reaches values of 33,56 MPa with the BONEM blade and 33,67 MPa with the BUSSOLA blade. In the cutter-blades, the maximum equivalent stress reaches values of 255,1 MPa with the BONEM blade and 241,5 MPa with the BUSSOLA blade. These results are similar to those obtained by Handong *et al.* (2011); Hu *et al.* (2016); Rezende (2020) and Qiu *et al.* (2021) with other varieties of sugar cane.

Figure 15 represents the behavior in time of the constant force components for the BONEM and BUSSOLA cutter blades, respectively. In both cases,

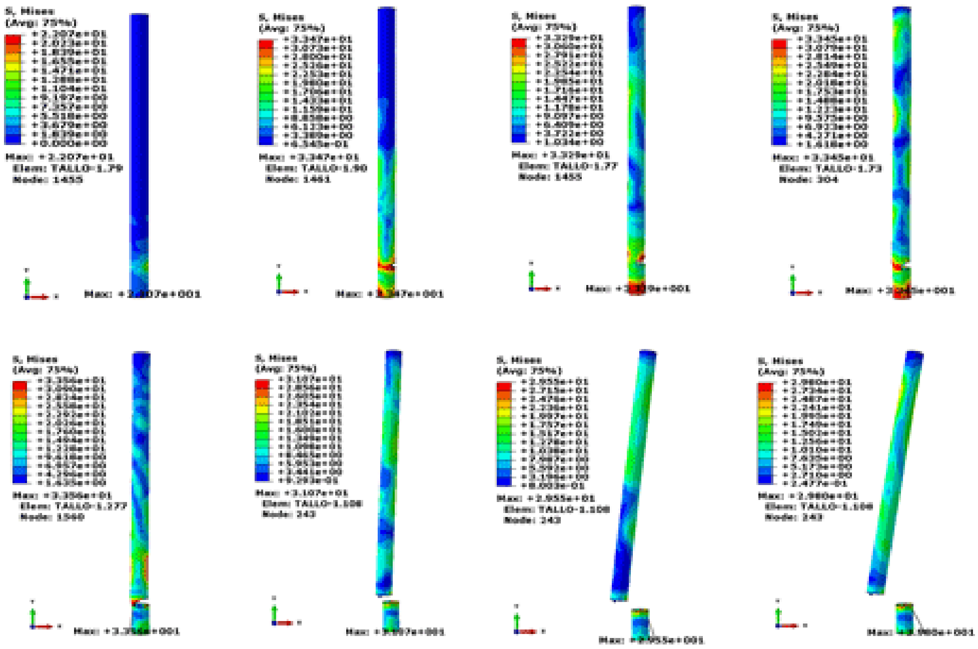


FIGURE 11. Stem stress nomograms for the BONEM cutter blade.

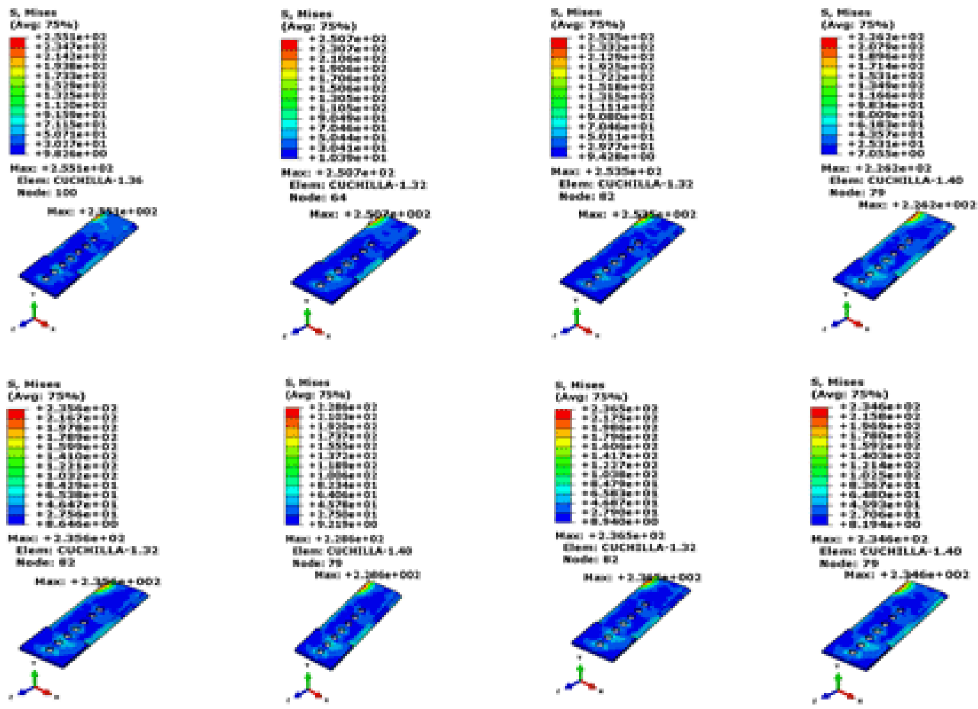


FIGURE 12. Stress nomograms in the BONEM cutter blade.

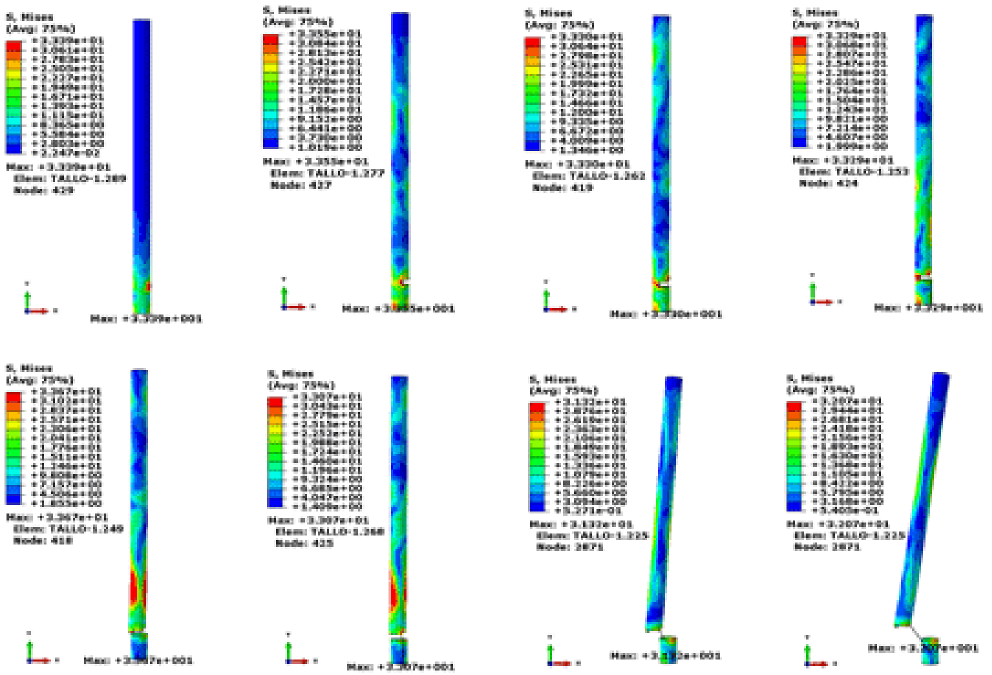


FIGURE 13. Stem stress nomograms for the BUSSOLA cutter blade

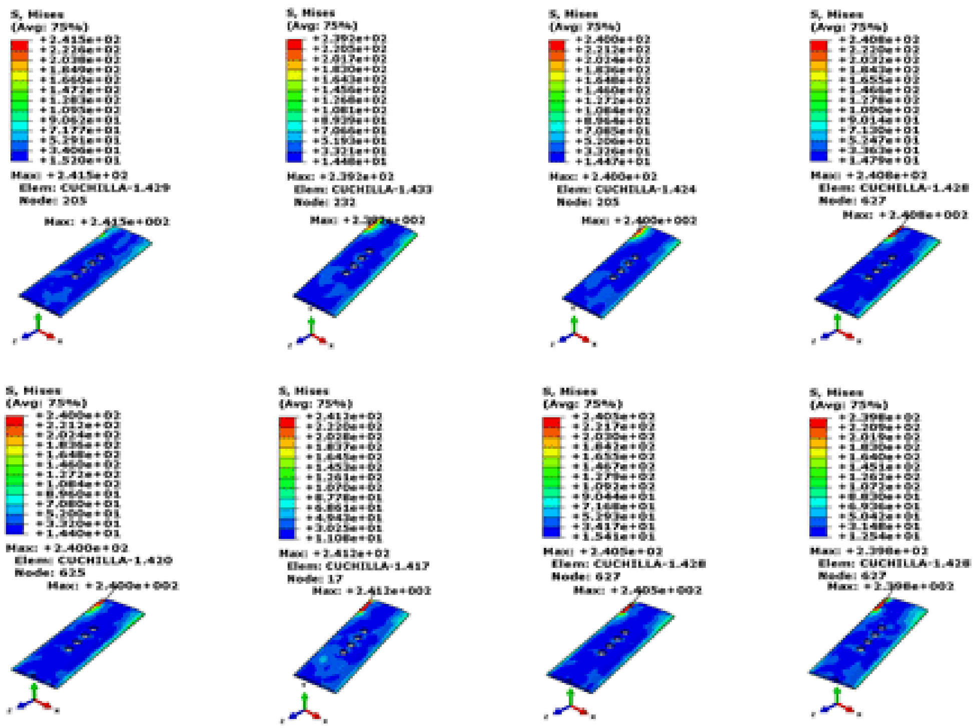


FIGURE 14. Stress nomograms in the BUSSOLA cutter blade.

the X direction represents the radial shear force, the Y direction the axial shear force, and the Z direction the circumferential shear force. During the normal cutting process, the radial and circumferential shear forces are small, while the axial shear force is the largest. Negative quantities indicate the reaction in the base cutter during the cutting process.

The magnitude of the cutting force with the BONEM blade reaches a maximum value of 508,291 N, higher than that of the BUSSOLA blade, which reaches 433,206 N. These results are in correspondence with those obtained by Taghijarah *et al.* (2012); Shen *et al.* (2016) and Xie *et al.* (2020) while they differ from those reached by Drees (2005);

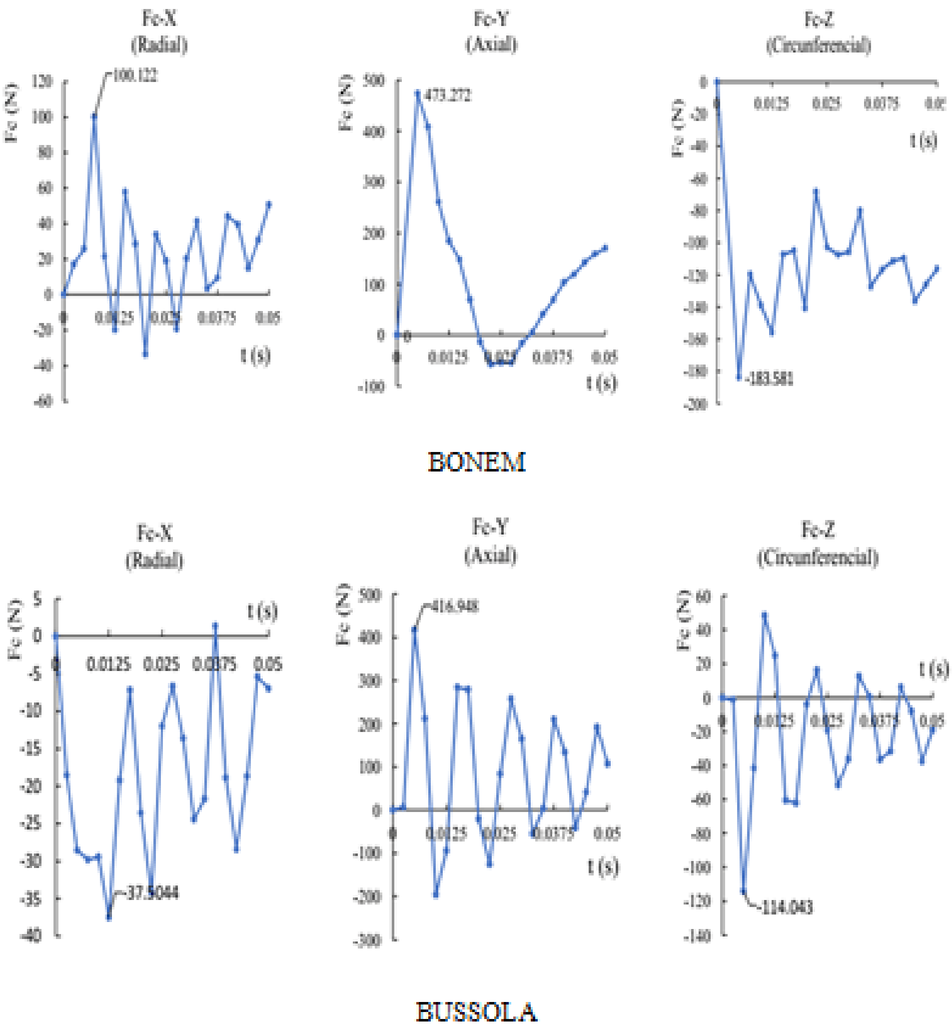


FIGURE 15. Behavior of the shear force components over time, for the BONEM and BUSSOLA cutter blades.

Gedam *et al.* (2015) and Abdallah *et al.* (2020) all with different varieties of sugarcane.

Figure 16 shows the Force-Displacement graphs obtained for both cutter blades with cutting speed of 65 rad/s and 0º of inclination of the base cutter, which correspond to those obtained by Srivastava *et al.* (1993); Guarnieri *et al.* (2007); Zastempowski & Bochat (2014) and Shen *et al.* (2016), in which the three characteristic stages of the cutting process can be appreciated: I - initial development stage of the cutting; II- stage of the deformation by cutting the cross section of the stem; III - post-cut stage.

In the Force-Displacement graph with the BONEM cutter blade, it is distinguished that in the initial development stage of the cutting (I), the magnitude of the cutting force increases from zero to a maximum value of 508,291 N, causing the process of cutting and destroying the stem structure. During the stage of deformation by cutting the cross section of the stem (II), the maximum value reached by the cutting force is 145,082 N, which gradually decreases with the progressive decrease of the cutting area to the value of zero in the moment when the stem is completely cut and the curve enters the region of the moment after the cutting (III). With the BUSSOLA cutter blade, in stage I, the magnitude of the cutting force increases from zero to a maximum value of 433,206 N, causing the cutting process and destroying the stem structure. During stage II, the maximum value reached by the cutting force is 290,961 N and when the stem is completely cut, the curve enters stage (III), where the cutting force is zero. As it can be seen, the initial development stage of the cutting with the BONEM blade reaches a greater displacement than with the BUSSOLA blade and the stage of shear deformation of the cross section of the stem, therefore, becomes smaller, which is influenced by the geometric difference that the tools have in relation to the angle of the cutting edge.

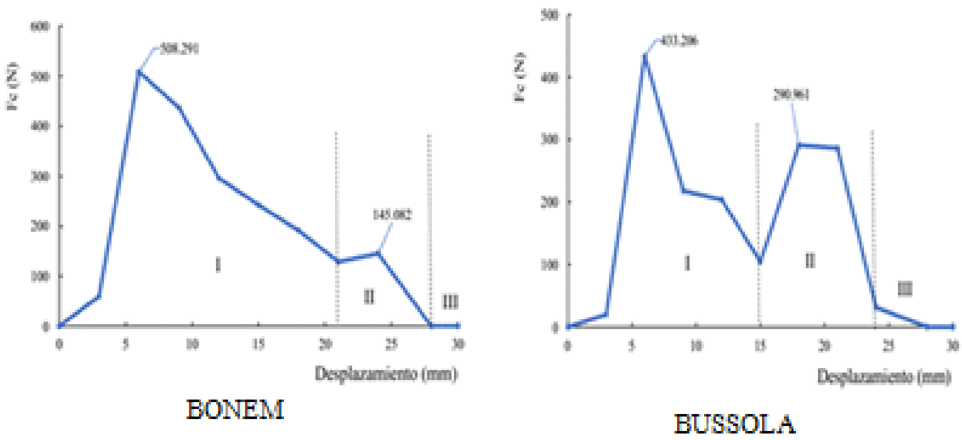


FIGURE 16. Force-Displacement graphs obtained for both cutter blades.

CONCLUSIONS

- The numerical methodology presented favors the study of the base cutting process of the sugarcane stems and contributes to reduce the number of experimental trials.
- The numerical model developed allows studying the influence of the main geometric and kinematic parameters of the base cutting process in sugarcane, since there is a good correspondence between simulation and experimentation, where it is observed that the magnitude of the error obtained between the experimental cutting energy test of variety C1051-73 with the BONEN blade and the validation numerical model is less than 5%.
- In the analysis of the five varieties of sugarcane studied, it is obtained that variety C90-469 is the one with the highest magnitudes of stress and reaction force in the stem and reaction moment in the base cutter for both cutter blades, which makes it the variety that has the greatest influence on the performance of these tools, while the C120-78 and C1050-73 varieties have the lowest magnitudes of these parameters and favor the behavior of the blades.
- During the cutting of a stem with average magnitudes of the physical-mechanical properties of the varieties studied, it is observed that the tension in the sugarcane during the cutting process is small and its maximum equivalent tension reaches values of 33,56 MPa with the BONEM blade and 33,67 MPa with the BUSSOLA blade. In the base cutter blade, the maximum equivalent stress reaches values of 255,1 MPa with the BONEM blade and 241,5 MPa with the BUSSOLA blade.

REFERENCES

ABADIA, R.L.A.: "La cosecha mecanizada de caña de azúcar. Apuntes básicos de mejoramiento", *[en línea]*, En: *Conferencia Red agrícola Trujillo-Perú, agosto, 2018*, Trujillo, Perú, 2018, *Disponible en:* https://www.redagricola.com/pe/assets/uploads/2018/08/1--luis-armando-abadia-optimizacion-de-cosecha-mecanica-de-cana-de-azucar.pdf, *[Consulta: 21 de octubre de 2019]*.

ABAQUS: *User's Manual, Ver. 6.14-1*, *[en línea]*, Hibbitt, Karlson and Sorensen, Inc., 2014, *Disponible en:* https://www.redagricola.com/pe/assets/uploads/2018/08/1--luis-armando-abadia-optimizacion-de-cosecha-mecanica-de-cana-de-azucar.pdf, *[Consulta: 21 de octubre de 2019]*.

ABDALLAH, M.Z.; EL-DEN; SAAD, F.A.; WALEED, M.H.; ABDALLAH, E.E.: "Review of some parameters related to the base-cutter of sugarcane harvesters", *Misr journal of Agricultural Engineering*, 37(4): 325-330, 2020, ISSN: 1687-384X, e-ISSN: 2636-3062, DOI: http://dx.doi.org/10.21608/mjae.2020.47247.1012.

CORTÉS, M.C.I.: *Propiedades mecánicas a tensión de las fibras del bagazo del Agave angustifolia Haw, residuo proveniente de la producción artesanal del mezcal*, Instituto Politécnico Nacional, Unidad Oaxaca, Tesis (en opción al título de Master en Ciencias), Oaxaca, México, publisher: Instituto Politécnico Nacional. Centro Interdisciplinario de Investigación …, 2009.

CRUZADO, A.; LEEN, S.; URCHEGUI, M.; GÓMEZ, X.: "Finite element simulation of fretting wear and fatigue in thin steel wires", *International Journal of Fatigue*, 55: 7-21, 2013, ISSN: 0142-1123, DOI: http://dx.doi.org/10.1016/j.ijfatigue.2013.04.025.

DOMÍNGUEZ, A.; MARTÍNEZ, R.; DE JUAN, J.; MARTÍNEZ, R.A.; TARJUELO, J.: "Simulation of maize crop behavior under deficit irrigation using MOPECO model in a semi-arid environment", *Agricultural Water Management*, 107: 42-53, 2012, ISSN: 0378-3774.

DONGDONG, D.; JUN, W.: "Research on mechanics properties of crop stalks: A review", *International Journal of Agricultural and Biological Engineering*, 9(6): 10-19, 2016, ISSN: 1934-6352.

DREES, A.M.: *A Study on Mechanization of Sugar Cane Planting, Fabricating a Seedling Preparation Unit and Performance Evaluation of Transplanting Machine for Sugar Cane Crop*, *[en línea]*, Mech. Dept., Ph.D. thesis Agric, 2005, *Disponible en:* https://www.erpublication.org/published_paper/IJETR022297.pdf, *[Consulta: 21 de enero de 2017]*.

GEDAM, K.; DESHMUKH, M.; THAKARE, S.: "Mechanical Properties of Sugarcane Stalk", *Madras Agricultural Journal*, 102(7-9): 281-284, 2015, ISSN: 0024-9602.

GUARNIERI, A.; MAGLIONI, C.; MOLARI, G.: "Dynamic analysis of reciprocating single-blade cutter bars", *Transactions of the ASABE*, 50(3): 755-764, 2007.

HANDONG, H.; YUXING, W.; YANQIN, T.; FENG, Z.; XIANGFA, K.: "Finite element simulation of sugarcane cutting", *Transactions of the CSAE*, 27(2): 161-166, 2011.

HU, D.F.; ZHENG, Y.F.; ZHAO, Y.: "Movement Simulation of Sugarcane Harvester Cutter Based on ANSYS/LS-DYNA", *[en línea]*, En: *International Conference on Engineering Science and Management (ESM)*, Ed. Atlantis Press, pp. 0268-0271, 2016, *Disponible en:* https://www.atlantis-press.com/proceedings/esm-16/25859574, *[Consulta: 21 de enero de 2018]*.

IZNAGA, B.A.M.; BRAUNBECK, G.O.A.: "Comportamiento físico-mecánico de un biomaterial sometido a bajas cargas", *Ingeniería Mecánica*, 14(1): 65-73, 2011, ISSN: 1815-5944.

KESTUR, S.G.; FLORES, S.H.; DOS SANTOS, P.; DOS SANTOS, I.; MAZZARO, I.; MIKOWSKI, A.: "Characterization of blue agave bagasse fbers of Mexico", *Applied Science and Manufacturing*, 45(1): 153-161, Composites Part A, 2012.

KROES, S.: *The cutting of sugarcane*, University of Southern Queensland, PhD diss., Toowoomba, Queensland, Australia, 1997.

MA, S.; KARKEE, M.; SCHARF, P.A.; ZHANG, Q.: "Sugarcane harvester technology: a critical overview", *Applied engineering in agriculture*, 30(5): 727-739, 2014, ISSN: 0883-8542.

MA, S.; SCHARF, P.; ZHANG, Q.; KARKEE, M.; TONG, J.; YU, L.: "Effect of cane stool density and stubble height on sugarcane stubble damage in Hawaii fields", *Transactions of the ASABE*, 59(3): 813-820, 2016, ISSN: 2151-0032, DOI: http://dx.doi.org/10.13031/trans.59.11334.

MELLO, R. da C.; HARRIS, H.: "Desempenho de cortadores de base para colhedoras de cana-de-açúcar com lâminas serrilhadas e inclinadas", *Revista Brasileira de Engenharia Agrícola e Ambiental*, 7(2): 355-358, 2003, ISSN: 1807-1929.

OTEGUI, M.E.; ANDRADE, F.H.; SUERO, E.E.: "Growth, water use, and kernel abortion of maize subjected to drought at silking", *Field Crops Research*, 40(2): 87-94, 1995, ISSN: 0378-4290.

PÉREZ, P.J.R.; SÁNCHEZ, J.R.; GUERRERO, P.J.N.; SANTILLÁN, M.C.J.: "Valoración de las Cargas en la Cosechadora de Caña de Azúcar en las Condiciones de Cuba", *European Scientific Journal*, 15(21): 294-303, 2019, ISSN: 1857-7881, e-ISSN: 1857-7431, DOI: http://dx.doi.org/10.19044/esj.2019.v15n21p294.

PÉREZ, R.R.A.: *Procedimiento para el análisis del desempeño de los segmentos de corte base de las cosechadoras de caña de azúcar CASE-IH*, Universidad de Ciego de Ávila (UNICA), Tesis (en opción al título de Doctor en Ciencias Técnicas Agropecuarias), Ciego de Ávila, Cuba, 145p., 2022.

QINGTING, L.; YINGGANG, O.; SHANGLE, Q.; WANZHANG, W.: "Stubble damage of sugarcane stalks in cutting test by smooth-edge blade [J]", *Transactions of the Chinese Society of Agricultural Engineering*, 23(3): 103-107, 2007.

QIU, M.; MENG, Y.; LI, Y.; SHEN, X.: "Sugarcane stem cut quality investigated by finite element simulation and experiment", *Biosystems Engineering*, 206: 135-149, 2021, ISSN: 1537-5110, DOI: https://doi.org/10.1016/j.biosystemseng.2021.03.013.

REZENDE, S.A.A.: *Simulação numérica aplicada ao corte basal dos colmos de cana-de-açúcar*, Universidade Federal de Lavras (UFLA), Dissertação apresentada no Programa de Pós-Graduação em Engenharia de Sistemas e Automação para a obtenção do título de Mestre, Lavras-MG, Brasil, 88 p., 2020.

SALDAÑA, R.A.; REVELES ARREDONDO, A.F.; SERWATOWSKI HLAWINSKA, H.R.J.; GUTIÉRREZ, V.C.; SALDAÑA, R.N.; LEDESMA, O.E.; CABRERA, S.J.M.: "Modelo de elemento finito para el corte de la fibra de Agave tequilana Weber", *Revista Ciencias Técnicas Agropecuarias*, 22(Especial): 15-21, 2013, ISSN: 1010-2760, e-ISSN: 2071-0054.

SHEN, C.; CHEN, Q.M.; LI, X.W.; TIAN, K.P.; HUANG, J.C.; ZHANG, B.: "Experimental analysis on single-stalk cutting of hemp.", *International Agricultural Engineering Journal*, 25(4): 187-196, 2016, ISSN: 0858-2114.

SILVA, S.L.; HERNANDEZ, G.L.H.; CABALLERO, C.M.; LÓPEZ, H.I.: "Tensile Strength of Fibers Extracted from the Leaves of the angustifolia Haw Agave in Function of their Length", En: *Applied Mechanics and Materials*, Ed. Trans Tech Publ, vol. 15, pp. 103-108, 2009, ISBN: 0-87849-309-3.

SRIVASTAVA, A.K.; GOERING, C.E.; ROHRBACH, R.P.; BUCKMASTER, D.R.: "Engineering principles of agricultural machines", *American Society of Agricultural and Biological Engineers*, 1993.

TAGHIJARAH, H.; AHMADI, H.; HEMATIAN, R.; SATTARI, N.A.M.: "Comparison of mechanical properties between two varieties of sugar cane stalks", *Elixir Mech. Eng.*, 42: 6415-6419, 2012, ISSN: 2229-712X.

TOLEDO, A. de; SILVA, R.P. da; FURLANI, C.E.A.: "Quality of cut and basecutter blade configuration for the mechanized harvest of green sugarcane", *Scientia Agricola*, 70: 384-389, 2013, ISSN: 0103-9016.

VALDÉS, H.P.A.; MARTÍNEZ, R.A.; AJALLA, R.; BRITO, R.E.; ALBÓNIGA, G.R.: "Influencia del ángulo de deslizamiento y la velocidad de la cuchilla sobre la energía específica durante el corte de tallos de caña de azúcar", *Revista Ciencias Técnicas Agropecuarias*, 18(1): 21-26, 2009, ISSN: 1010-2760, e-ISSN: 2071-0054.

VALEIRO, A.; BIAGGI, C.: *Revisión crítica de la evolución tecnológica de la cosecha de la caña de azúcar en la Argentina"*, Revisiones- RIA, Trabajos en prensa, 2019.

XIE, L.; WANG, J.; CHENG, S.; DU, D.: "Cutting Characteristics of Sugarcane in Terms of Physical and Chemical Properties", *Transactions of the ASABE*, 63(4): 1007-1017, 2020, ISSN: 0001-2351.

YUAN, F.; YANG, W.; YANG, J.; MENG, H.; WU, L.; NONG, H.; GUO, W.: "Numerical Simulation of Sugarcane under Wind Load", En: *IOP Conference Series: Materials Science and Engineering*, Ed. IOP Publishing, vol. 187, 2017, DOI: http://dx.doi.org/10.1088/1757-899X/187/1 / 012024.

ZASTEMPOWSKI, M.; BOCHAT, A.: "Modeling of Cutting Process by theShear-Finger Cutting Block", *Applied Engineering in Agriculture*, 30(3): 347-353, 2014, ISSN: 0883-8542.

Rigoberto Antonio Pérez Reyes, Profesor Auxiliar, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba. Carretera a Morón km 9½, CP: 65 300, Teléfono (33) 21 7009, Fax 53 33 225768, e-mail: rigobertopr@unica.cu.
Lázaro Antonio Daquinta Gradaille, Profesor Titular, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba. Carretera a Morón km 9½, CP: 65 300, Teléfono (33) 21 7009, Fax 53 33 225768, e-mail: daquintagradaille@gmail.com
Jorge Douglas Bonilla Rocha, Profesor, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba. Carretera a Morón km 9½, CP: 65 300, Teléfono (33) 21 7009, Fax 53 33 225768, e-mail: jorgedbr@unica.cu.
Carlos Alexander Recarey Morfa, Profesor Titular, Universidad Central de las Villas, Santa Clara, Villa Clara, Cuba, e-mail:: recarey@uclv.edu.cu.
Anibal Sánchez Numa, Profesor, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba,. Carretera a Morón km 9½, CP: 65 300, Teléfono (33) 21 7009, Fax 53 33 225768, e-mail: anibal@unica.cu.
Julio Eustaquio Gómez Bravo: Profesor, Universidad de Ciego de Ávila Máximo Gómez Báez, Facultad de Ciencias Técnicas, Ciego de Ávila, Cuba. Carretera a Morón km 9½, CP: 65 300, Teléfono (33) 21 7009, Fax 53 33 225768, e-mail: julioe@unica.

AUTHOR CONTRIBUTIONS: Conceptualization: R. A. Pérez. **Data curation:** R. A. Pérez, L. A. Dquinta. **Formal analysis:** R. A. Pérez, L. A. Dquinta, J. D. Bonilla, C. A. Recarey, A. Sánchez, J. E. Gómez. **Investigation:** R. A. Pérez, L. A. Dquinta, J. D. Bonilla, C.A. Recarey, A. Sánchez, J. E. Gómez. **Methodology:** R. A. Pérez, L. A. Dquinta, J. D. Bonilla, C.A. Recarey, A. Sánchez, J. E. Gómez. **Project administration:** L. A. Dquinta, R. A. Pérez. **Software:** R. A. Pérez, J. D. Bonilla, C. A. Recarey, A. Sánchez. **Supervision:** R. A. Pérez. **Validation:** R. A. Pérez, L. A. Dquinta, J. D. Bonilla. **Roles/Writing, original draft:**R. A. Pérez. **Writing, review & editing:** L. A. Dquinta, J. D. Bonilla, C.A. Recarey, A. Sánchez, J. E. Gómez.

The authors of this work declare no conflict of interest.

The mention of commercial equipment marks, instruments or specific materials obeys identification purposes, there is not any promotional commitment related to them, neither for the authors nor for the editor.