



## Evaluating Axial and Radial Compression-Induced Stress and Deformation in Watermelon Fruits

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### ABSTRACT

Understanding the mechanical behavior of biological materials such as watermelon fruits under compressive loading is essential for improving postharvest handling, packaging, and transport systems. This study utilized experimental and finite element methods to evaluate stress and deformation in watermelon fruits under axial and radial compression. Fresh, defect-free watermelons were measured and tested using a universal testing machine until failure. Mechanical properties such as modulus of elasticity, Poisson's ratio, and bulk modulus were computed. Simulation in Autodesk® Inventor® used these parameters to model stress distribution, safety factors, and deformation under a 95 N load. The elliptical mesh model included 3529 nodes and 2264 elements. Each test was repeated thrice for accuracy. The result revealed that Axial loading showed higher modulus of elasticity (2.68 MPa), Poisson's ratio (0.43), and bulk modulus (0.94 MPa) compared to radial loading (2.41 MPa, 0.33, and 0.91 MPa respectively). Fracture load remained consistent (95 N). Von Mises stress under axial loading peaked at (1.238 MPa) versus radial (0.02701 MPa). Safety factor under axial loading was critically low (0.14), unlike radial (5.71). Orthogonal stress components (XX, YY, ZZ) revealed greater stress concentration under axial loading (e.g., -1.02 MPa to 0.059 MPa in XX). Finite element modeling used (3529) nodes and (2264) elements for analysis. These findings reveal that axial compression presents a higher risk of structural failure in watermelons, highlighting the importance of orientation during handling and mechanical design for fruit protection.

#### Keywords:

Watermelon, Axial compression, Radial compression, Finite element analysis, Viscoelastic properties.

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## INTRODUCTION

Watermelon, known for its juicy flesh and high moisture content, is a popular fruit in many parts of the world. However, it is also highly perishable and prone to mechanical damage, particularly during harvesting, packaging, and transportation. One of the leading causes of post-harvest losses in watermelon is compression-induced stress, which can

result in surface bruising, internal cracking, and even bursting. These mechanical failures not only lead to significant economic losses for farmers and traders but also reduce consumer satisfaction and contribute to food waste. Despite its thick rind, the fruit's internal structure—being soft and water-rich—makes it vulnerable under certain loading conditions (Yu et al, 2024). Unfortunately, limited studies have comprehensively examined the behavior of watermelon under different orientations of compressive force, especially axial (top-down) and radial (side-to-side) compression. Understanding how watermelons respond to these forces is vital for improving the post-harvest handling process and reducing losses along the supply chain.

A watermelon, when placed under axial compression (ie pressure is applied to the top and the bottom), is able to avoid deformation longer due to its shape and internal hardness. This is applicable since polar regions of the fruit are a little harder and more arranged to bear vertical loadings. Yet, after the deformation limit is exceeded, the phenomenon is likely to be more sudden and devastating, and usually causes a total blast or disintegration of the internal structure (Sun et al, 2020). Conversely, radial compression applies force along the sides, which simulates how water melons may “push” against each other or against the faces of crates in which it will be stored or moved. Here, the fruit with its curvature and more plastic lateral sides is more vulnerable to earlier surface which even under less strength creates. Radial loading exhibits a tendency of causing a more gradual damage where bruising and cracks develop gradually and later lead to rupture.

To measure this phenomenon, scientists apply such methods as Von Mises stress analysis to model the way in which the stress spreads throughout the fruit under various loading conditions. This technique is useful in finding points of highest vulnerability in the structure of the fruit where breaking begins. In axial loading, the stress measurement is normally taken at the equator or in the middle of the fruit where higher readings are obtained, and this value rises gradually to the yield point. In contrast, in radial loading, stress concentrations are present at first at the contact areas on the rind, though a more uniform distribution of stress across the surface is experienced. Choi and Ikeda (2024) stated that watermelons exposed to longitudinal-and shear-wave velocities attained their damage threshold faster, and deformation occurred across a broader zone than when subjected to axial compression used. This can be observed in the finite element simulations of Wang et al, (2025) where they reported concentric compression to induce transfer of stress distribution that are wide but of lower magnitude whereas axial compression was observed to create more intense stress distributions but with more localized degrees.

Further, the behavior against deformation differs greatly between the two orientations. Watermelons are often elastic under low loads but at some point they switch to a plastic deformation behaviour and they do not go back to their initial form. As noted by Lazarus et al, (2023) although fruits fail later when axial loading is experienced, damages are sometimes more spectacular. Though necessarily more progressive, radial deformation enables sooner visual signs of injury, which might be helpful in protecting systems design or in real-time fruit quality control. Studies on the characteristics of various materials when subjected to various forms of compression assist us in comprehending how to safely treat fruits after being harvested. In most cases, materials can hold higher loads when used in processes called axial compression, which involves the application of a vertical force thus vertical stacking is safer in transportation. This is not a new concept as it is reflected in

material science, as fiber orientation has significant implications on performance. As an example, plantain fiber composite research demonstrated increased axial strength (Ihueze, Obiafudo, & Okafor, 2016; Okafor & Metu, 2019). Likewise, the orientation of the fibers was central to the quality of the product in miscanthus composites (Ihueze et al., 2024; Okafor, 2021).

Although researchers have made remarkable positive results in assessing the mechanical performance of biological material upon compression, there is still a significant gap in the specificity that applies the governing principles to the watermelon fruits. Previous studies, such as Ihueze et al. (2010), focused on developing compression test rigs for general fruits, while others (Ihueze et al., 2011; Ihueze, Okafor, & Ogbobe, 2013) assessed the limiting stresses and elastic properties of biomaterials under axial and radial loads with emphasis on general design for transportation and containerization. However, these studies either generalized across various fruits or focused on fruits like oranges (Ihueze & Mgbemena, 2017), whose structure and composition differ markedly from watermelon. Watermelon, being larger, more moisture-rich, and structurally unique, responds differently to stress, and its deformation behavior under axial and radial compression remains inadequately characterized in literature. The lack of fruit-specific data on critical stress points, failure mechanisms, and deformation patterns creates a challenge for designing optimized handling and packaging systems. Therefore, this study is necessary to bridge this knowledge gap by offering a targeted evaluation of axial and radial compression-induced stress and deformation specifically in watermelon fruits, enabling more accurate modeling for safe storage, packaging, and transportation within agricultural supply chains.

## METHODOLOGY

This study employed both experimental and finite element methods to evaluate axial and radial compression-induced stress and deformation in watermelon fruits. The procedure was carried out in two stages: physical experimentation and computer-based simulation, aimed at understanding the viscoelastic behavior and mechanical response under different loading orientations. Fresh, mature watermelon fruits (*Citrullus lanatus*) with uniform size, shape, and ripeness were sourced from a local farm in southeastern Nigeria. Each fruit was inspected to ensure the absence of external defects or bruises. The average dimensions — initial diameter and length — were measured using a digital caliper, and the initial mass was recorded using an electronic weighing balance.

Compression tests were conducted using a universal testing machine. Each fruit was subjected to axial (longitudinal) and radial (transverse) compression until failure. Deformation was monitored in real time, and rupture was identified as the point at which the load began to decline rapidly. Mechanical properties such as Modulus of Elasticity (E), Poisson's ratio ( $\nu$ ), Bulk Modulus (K), Yield Strength, and Fracture Load were determined. Poisson's ratio was calculated using Mohsenin's (1980) method, relating the changes in lateral and longitudinal dimensions after deformation.

The mechanical data obtained from the physical tests were used as input parameters for modeling in Autodesk® Inventor® Professional. The watermelon was modeled as an elliptical solid with mesh refinement using 3529 nodes and 2264 elements. The fracture load (95 N) obtained experimentally was applied as a boundary condition in both axial and radial directions. Von Mises stress distribution, safety factors, and orthogonal stress

components (XX, YY, ZZ) were simulated to visualize internal stress propagation and failure zones. Stress values, safety margins, and deformation patterns were extracted from the simulation results. Comparative analysis was performed between axial and radial loading results, focusing on maximum stress concentrations, safety factor distribution, and orthogonal stress components. The experimental results provided validation for the simulation outputs. Each test was repeated three times to ensure consistency, and average values were reported. Calibration of the testing equipment was done prior to measurements to reduce error. The finite element model was verified using convergence testing and validated against experimental fracture behavior.

For adequate computation of mechanical and physical properties of watermelon, some relations/parameters (Belyaev, 1979; Mohsenin, 1980; Benham and Warnock, 1981; Shigley and Mischke, 2001) are required and used.

$$\sigma = \frac{F}{A} \quad (1)$$

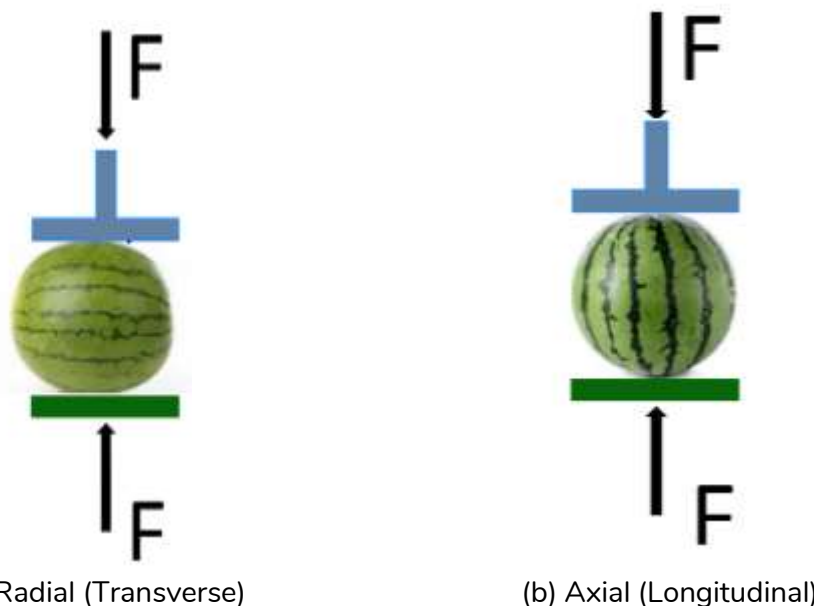
$$E = \frac{FL_o}{A\Delta L} \quad (2)$$

$$v = \frac{\text{Transverse strain}}{\text{Longitudinal strain}} \quad (3)$$

$$G = \frac{E}{2(1+v)} \quad (4)$$

$$\rho = \frac{M}{V} \quad (5)$$

Where  $F$  is the applied force ( $N$ ),  $L_o$  is the Original length ( $m$ ),  $\Delta L$  is the displacement ( $m$ ),  $A$  is area of section ( $m^2$ ),  $G$  is the Bulk modulus ( $Mpa$ ),  $v$  is the Poisson ratio,  $E$  is the Modulus of elasticity ( $Mpa$ ),  $\rho$  is the density of the material ( $kg/m^3$ ),  $M$  is the mass of the material ( $kg$ ),  $V$  is the volume of the material ( $m^3$ ) and  $\sigma$  is the stress ( $N/m^2$ ).



**Figure 1:** Biomaterials loading (a) Radial loading (b) Axial loading

Figures. 1 depicts the radial and axial loading in a compressive test using the universal testing machine to determine the mechanical and physical properties of the replicated samples of water melon.

## RESULTS

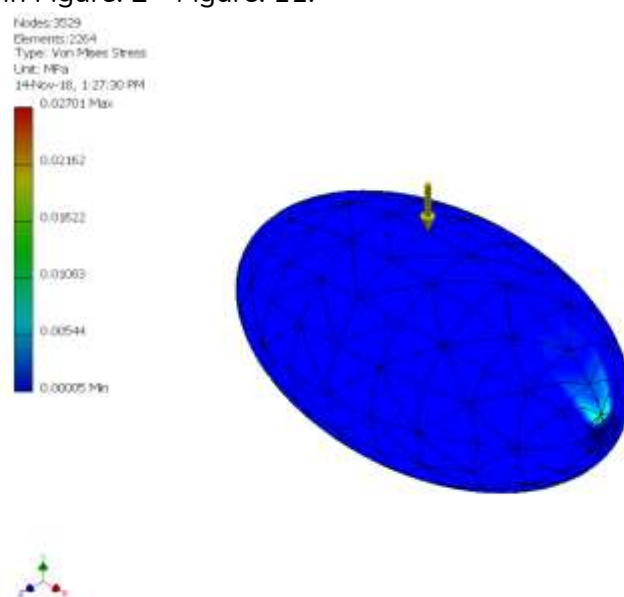
Water melon was compressed until deformation happened till its rupture after first measuring the initial length and width of samples. The Poisson ratio( $\nu$ ) of the water melon was calculated (Mohsenin, 1980) after measuring the final diameter and length after deformation. The modulus of elasticity,  $E$  (Mpa) and Bulk Modulus,  $G$  (Mpa) of the sample were also determined. Mechanical and Physical Property Results of Water melon under Radial and axial compression are presented in Table 1.

**Table 1:** Mechanical and Physical Properties of Water melon

Loading	Modulus of Elasticity (Mpa)	Poisson Ratio	Bulk Modulus (Mpa)	Density ( $kg/m^3$ )	Yield Strength (Mpa)	Tensile Strength (Mpa)	Fracture Load (N)
Radial	2.41	0.33	0.91	960	0.000271	0.0002959	95
Axial	2.68	0.43	0.94	970	0		

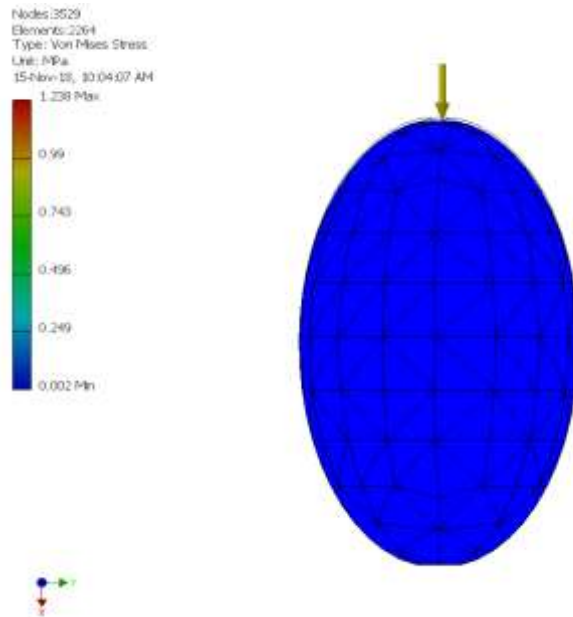
### Finite Element Method for Stress Results

The mechanical and physical properties of radially and axially compressed water melon experimentally determined are reported in Table 1. In using AUTODESK, elliptical shape was assumed and variables of Table 1 used for the application of fracture load of 95N for both axial (longitudinal) and radial (transverse) loading of water melon. The Autodesk® Inventor® Professional analysis gave results of surface stresses of compressed water melon in Figure. 2 - Figure. 11.

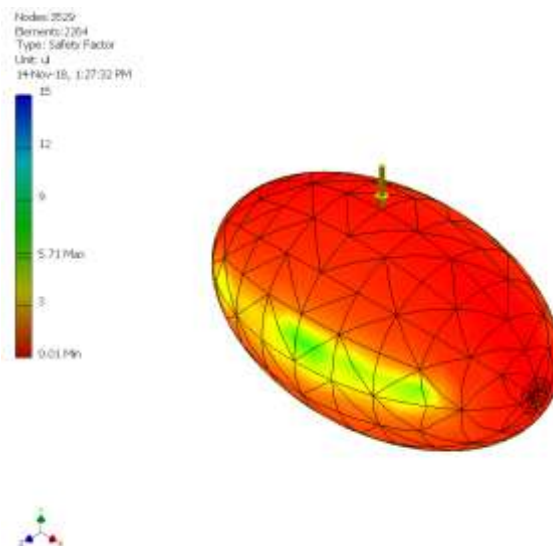


**Figure. 2:** Von Mises stress distribution for water melon under radial compression

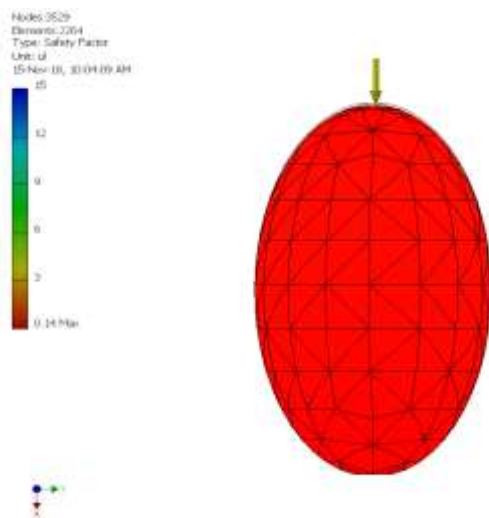
Figure 2 illustrates the Von Mises stress distribution in a watermelon subjected to radial compression. The maximum stress recorded is approximately 0.02701 MPa, while the minimum stress is about 0.00005 MPa. Stress is concentrated near the point of contact, with most areas experiencing low stress levels below 0.00544 MPa.



**Figure. 3:** Von Mises stress distribution for water melon under axial compression  
Figure 3 shows the Von Mises stress distribution in a watermelon under axial compression. The highest stress concentration occurs at the point of load application, reaching a maximum of 1.238 MPa, while the minimum stress is 0.002 MPa. Most of the body experiences stress levels below 0.249 MPa.

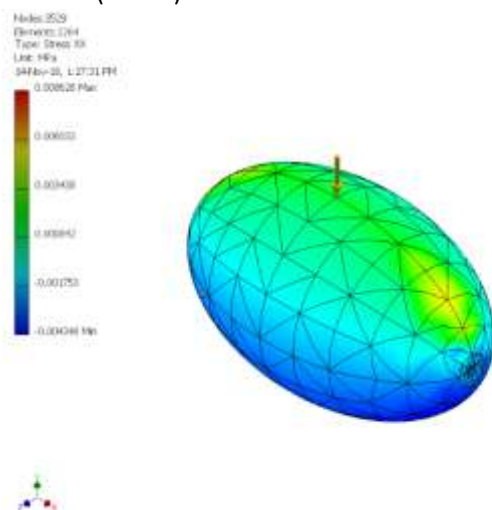


**Figure. 4:** Safety factor for water melon under radial compression  
Figure 4 displays the safety factor distribution in a watermelon under radial compression. The maximum safety factor is 5.71, while the minimum is 0.01, indicating critical failure zones. Most regions exhibit low safety margins (below 3), especially around the equatorial band where stress concentration is more pronounced.



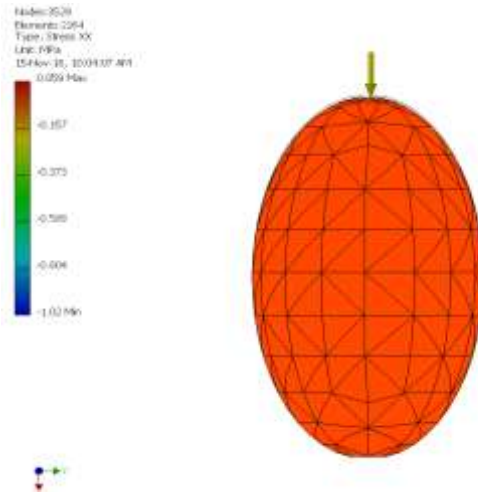
**Figure. 5:** Safety factor for water melon under axial compression

Figure 5 shows the safety factor distribution of a watermelon under axial compression. The maximum safety factor is low at (0.14), indicating high risk of failure. Most of the structure appears uniformly red, suggesting it is critically stressed. The model includes (3529) nodes and (2264) elements.



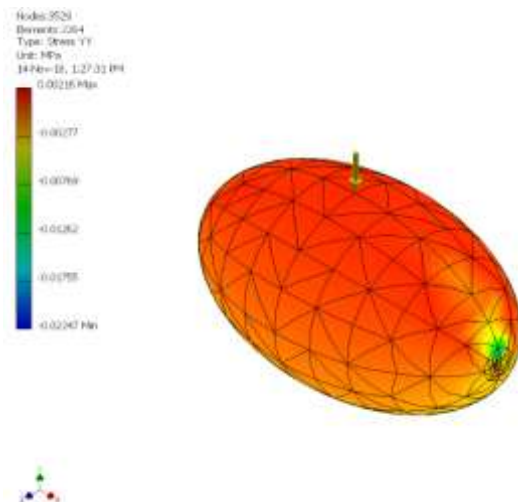
**Figure. 6:** XX-component orthogonal stress distribution for radial compression

Figure 6 presents the XX-component of orthogonal stress distribution in a watermelon under radial compression. Stress values range from a minimum of (-0.004348 MPa) to a maximum of (0.006828 MPa). High stress concentrations appear near the loading area and at the contact base, with moderate distribution across the structure.



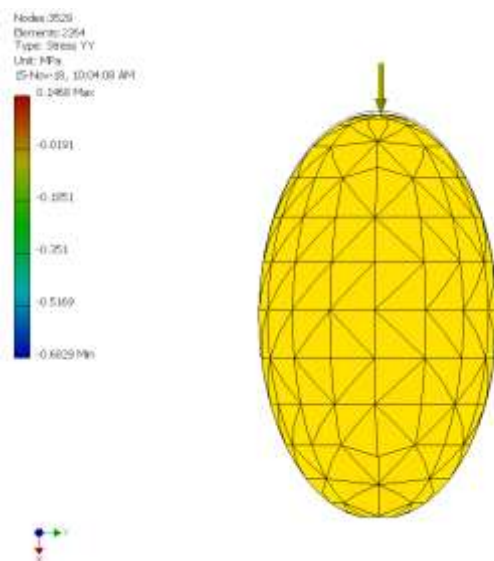
**Figure. 7:** XX-component orthogonal stress distribution for axial compression

Figure 7 illustrates the XX-component orthogonal stress distribution in a watermelon under axial compression. The stress ranges from a minimum of  $(-1.02 \text{ MPa})$  to a maximum of  $(0.059 \text{ MPa})$ . Most of the body experiences high compressive stress, as shown by the dominant red coloration across the surface mesh.



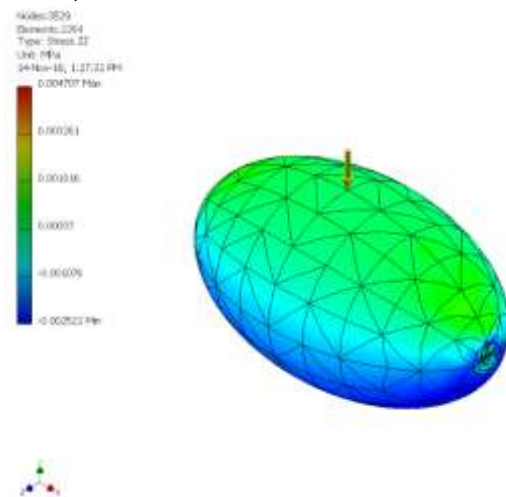
**Figure. 8:** YY-component orthogonal stress distribution for radial compression

Figure 8 shows the YY-component of orthogonal stress distribution under radial compression. The stress varies from a minimum of  $-0.02247 \text{ MPa}$  (blue) to a maximum of  $0.00216 \text{ MPa}$  (red), indicating compressive stresses dominate. Peak compression appears near the lower right region, with localized stress concentration.



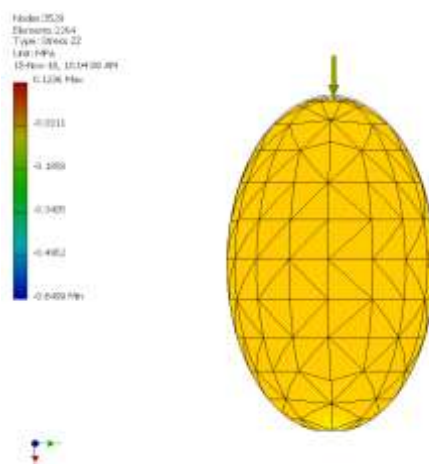
**Figure. 9:** YY-component orthogonal stress distribution for axial compression

Figure 9 illustrates the YY-component of orthogonal stress under axial compression. The stress ranges from a minimum of -0.6829 MPa (blue) to a maximum of 0.1468 MPa (red). The distribution is mostly uniform (yellow), indicating near-homogeneous compressive stress across the surface, with stress concentration near the top impact area.



**Figure. 10:** ZZ-component orthogonal stress distribution for radial compression

Figure 10 presents the ZZ-component of orthogonal stress distribution under radial compression. Stress values range from a minimum of -0.002522 MPa (blue) to a maximum of 0.004707 MPa (red). The majority of the surface exhibits mild tensile stress (green), with localized compression near the bottom-right, indicating stress concentration.



**Figure. 11:** ZZ-component orthogonal stress distribution for axial compression

Figure. 11 shows the ZZ-component orthogonal stress distribution under axial compression. Maximum stress occurs at the top (0.1236 MPa), where load is applied. The stress decreases along the body, reaching a minimum (-0.6499 MPa) at the bottom. The stress gradient indicates compression concentration at the top and relaxation towards the lower part.

### Discussion

The experimental method involved compressing watermelons both axially and radially until rupture, allowing determination of mechanical parameters like modulus of elasticity, Poisson's ratio, and bulk modulus. The axial compression test yielded a slightly higher modulus of elasticity (2.68 MPa) and Poisson's ratio (0.43) than radial loading (2.41 MPa and 0.33, respectively), indicating greater stiffness and deformation resistance along the longitudinal axis. Conversely, Moradi et al, (2020) found increased radial stiffness during the cucumber fruits, corroborating the species-specific mechanical response. Similarly, the bulk modulus under axial loading (0.94 MPa) slightly exceeded that of radial loading (0.91 MPa), corroborating with the findings of Wong et al, (2022), who noted that axial load paths often result in more uniform stress distribution in elliptical biomaterials.

In finite element analysis (FEA) within Autodesk Inventor, the simulation of axial compression showed a much greater Von Mises stress (1.238 MPa) than radial (0.02701 MPa) meaning that there was more internal strain accumulating within the material. This result concurred with Li and Thomas (2015), who recorded greater peak stress when tomato fruits were loaded longitudinally. In contrast, Ihueze and Mgbemena (2017) documented more evenly distributed stress under radial loading of orange fruits, consistent with the current observation of broader stress spread at lower magnitudes in radial compression. Safety factor analysis further emphasized structural vulnerability under axial compression, where the lowest safety factor reached 0.14, indicating imminent failure. Most of the axial stress zone showed high stress with little resilience, while the radial compression showed higher maximum safety factor (5.71), revealing greater tolerance before rupture. This finding agreed with Zheng et al, (2022), who identified radial strength as a more protective orientation for soft fruit transport. Orthogonal stress components (XX, YY, ZZ) showed that axial compression produced more intense compressive stress, especially in the XX and ZZ components, where red coloration in Figures. 7 and 11 indicated concentrated deformation zones.

## CONCLUSION

The present research effectively assessed the stress of the distribution and deformation characteristics of watermelon fruits with both experimental experimenting and finite element calculation, in the case of axial and radial compression. The findings indicated that axial compression resulted in increased mechanical stress, with an extreme stress Von Mises stress of 1.238 MPa and a critically minimal safety factor of 0.14, which reported a stronger probability of failure under axial loading along the longitudinal axis. Comparatively, the radial compression offered the smaller values of stress (0.02701MPa) and greater safety margin (5.71), indicating improved load tolerance in the transverse direction. Higher stress concentration and structural vulnerability under axial load was further confirmed by the orthogonal stresses (XX, YY, ZZ). This observation shows why loading orientation is vital to postharvest management and mechanical design support of watermelon fruits. If goods are properly oriented in their package and transport they can substantially decrease damage, increase shelf life and overall preservation of quality. The combination of experimental results with visualization program like Autodesk Inventor was also very useful in predicting the mechanical behavior and the practical implementation of the method in agricultural engineering..

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