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Date Palm Rachis as a Local and Renewable Structural Material for Rural Communities in Egypt

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Abstract

Date Palm Rachis has been widely used in sheathing of houses in the rural communities in Egypt and the Middle East, as a local and cheap material that naturally resists direct solar radiation and humidity. Lately, researchers around the world began to build complete structures using Date Palm Rachis to take advantage of its abundance and natural resistance. However, due to the lack of the required mechanical properties for structural analytical modeling, mock ups are used to assess the structural properties of Date Palm Rachis. This tool of assessment is insufficient in the consideration of wind or temporary and unforeseen loads. This paper introduces the closest estimations of the complicated mechanical properties required for structural analytical modeling, according to the available equipment and the variable nature of Date Palm Rachis. The results showed that Date Palm Rachis is a promising structural material with structural properties that are competitive to that of imported timbers in Egypt. This paper invites researches and builders to exploit the potentials of Palm Rachis as a structural material for rural communities.

Keywords

Date Palm Rachis; Mechanical Properties; Natural Structural Material

1. Introduction

The increasing costs of the conventional building materials, such as concrete and steel, led to the dependence on junk and scrap to build houses in poor communities in Egypt. The governmental efforts to solve the problem of this informal construction trend require long-term financial support that is not guaranteed under the circumstances of the high inflation rate and the global economic crisis. Exploring natural building materials and local building materials in a society provides a new chance in the local development that is driven from the inside. Mudbrick is one of the common building materials used to build houses in the rural communities, and famous architects have tried to revive this history (Fathy, 1993). Lately, more attention has been paid to agricultural residues to be the new building material that solves the problem of the decrease of the soil fertility that is required to make the mudbricks (Kennedy, 2004). One of the most abundant residues in Egypt and the Middle East is Date Palm Rachis (Elmously, 2005).

The dried date palm parts and the date palm main components are illustrated in figure 1 and 2.

Date palm rachis has been used as a building material in rural areas in Egypt and the Middle East. This technical heritage has accumulated over centuries due to the abundance of the highly renewable date palm rachis, as date palm rachis is the most available pruning residues of Date Palm Trees that cover the vast area of the deserts, oases and the Nile Valley, as shown in Table 1 (Elmously, 2005).

Table 1. Statistics of Date Palm Pruning Residuesin Egypt (Elmously, 2005)

Quantity Available annually (air dry weight-10% moisture content	Palm Rachis	Palm leaflet	Stem	Coir	Petiole	Total (ton/year)
Per palm, kg (mature female)	9.75	8.00	7.00	1.25	4.4	30.4
Total in Egypt, thousand tons	105.3	86.4	75.6	13.5	86.4	328.3

Traditionally, rural houses, eco-lodges and public places combined date palm rachis and date palm trunks to build roofs. In Sinai, date palm rachis is accumulated in layers to make exterior sheathing for the roofs with thicknesses that exceeds 20 cm to shield the houses from the direct sunlight, as illustrated in Figure 3 (Ibrahim, 2010). In Siwa and the western oases, date palm trunks are halved and used as ceiling beams, where Date Palm Rachis is used as a sheathing material that will enhance the interior design of the ceiling, as illustrated in Figure 4 (Alamuddine, 2001). In temporary structures in the Nile valley such as shades, date palm rachis is threaded to make walls and roofs that are fastened to small tree stems which work as columns and beams in the corners (Elmously, 2001).

Figure 1. Dried Date Palm Main Parts (Mahdavi, 2010)

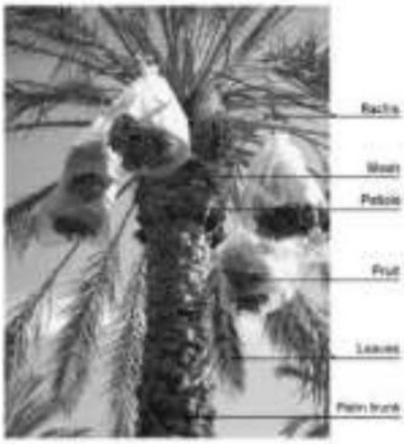

Figure 2. Date Palm Main Components

Figure 3. Palm Trunk Beams used for traditional roofing in Sinai (Ibrahim, 2010)

Figure 4. Roofing by Palm Rachis Adrere Amellal Eco-Lodge (Alamuddin, 2001)

Figure 5. Date Palm Rachis Walls in Arish House (Piesik, 2012)

Figure 6. Date Palm Rachis walls and roofs in Arish House (Piesik, 2012)

This increasing dependence on date palm rachis as a structural material led to previous research that push the limits of date palm rachis as an independent structural material to build cheap and fast shades. These experiments depended solely on building full scale mock-ups of the proposed shades due to the lack of mechanical properties of palm rachis that are required for the structural analysis, although this could help to expect static loads, wind, seismic loads and the limits of the spans of the proposed structures. The first pioneering experiment was based on a proposal of gathering date palm rachis as bundles that are formed as arches. Those arches were planted in the wet soil at spacing of 5m, while covering a span of 13m. As revolutionary as it sounds, the structure succeeded in covering the span, but only after using palm trunks as intermediate columns along every arch on intervals of 3.25 m. Hence, the onsite decision led to construct a shade with a span that is actually only 3.25 m (Piesik, 2012). Figure 7 pictures the vault during construction, while Figure 8 illustrates the interior columns that were closely spaced. The connection used was rope-based connection (Figure 9).

Figure 7. The Vault during Construction (Piesik, 2012)

Figure 8. Interior Columns (Piesik, 2012)

Figure 9. Rope based Connections (Piesik, 2012)

Another experiment using date palm rachis to build shades was based on the structural concept of ring beams.

Date palm rachis were gathered to make curved bundles that are planted along the parameter of the proposed circle to cover. Then, a plywood ring was made to attach the edges of the curved bundles. However, the height of the structure decreased due to the deflection that happened under the weight of the final sheathing, as illustrated in Figures 10 to 12 (”Turn Over a New Leaf”, 2013).

Figure 10. Ring beam in structure (Boisbushet, 2013)

Figure 11. Structure after completion (”Turn Over a New Leaf”, 2013)

Figure 12. Deformation after sheathing (”Turn Over a New Leaf”, 2013)

Therefore, it can be concluded from the previous literature review, that building shades using date palm rachis while depending solely on building real mock-ups is not sufficient to predict onsite behavior and unexpected loads such as sheathing weight, wind and seismic loads. Therefore, this paper aims to introduce the closest estimation of the mechanical properties of date palm rachis, according to the natural variations of date palm rachis and the available equipment in the laboratories of Faculty of Engineering, Ain Shams University.

2. Material and Methodology

Previous research showed that the properties of date palm rachis are competitive to imported wood species, specifically those of spruce wood (Elmously, 2001). However, due to the complexity of the variable nature of date palm rachis, those previous studies only measured some of the longitudinal properties for the whole date palm rachis regardless of the other two dimensions, as date palm rachis is considered an anisotropic material (Figure 13).

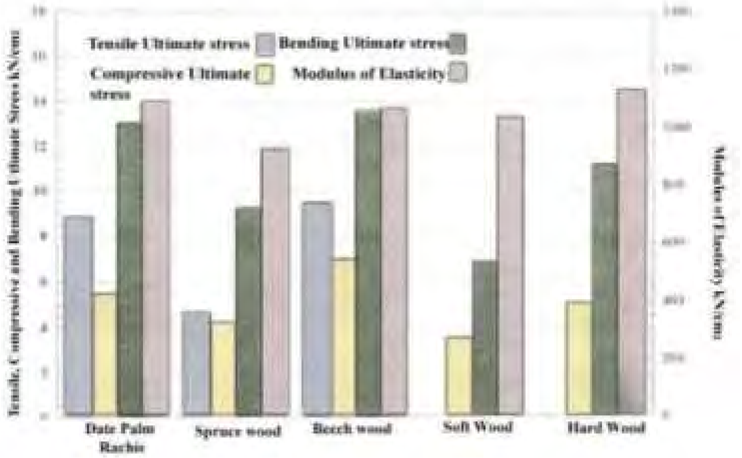

Figure 13. Comparison between the mechanical properties of Palm Rachis and imported wood and their standard values in ASTM D2555-88 (Elmously, 2001)

In nature, materials are classified into isotropic, orthotropic, and anisotropic materials. Isotropic materials are the materials where the mechanical properties are identical in all directions, such as glass and metals. On the other hand, the properties of fibrous materials such as timber vary according to the fiberds' direction, which makes them anisotropic materials (Mascia, & Lahr, 2006). However, in engineering elastic models timber is considered an orthotropic material.

The linear orthotropic model suggests three planes of symmetry in the following three directions: longitudinal, radial and tangential, which are coincident with the three Cartesian directions: x, y and z. Where longitudinal direction of timber is parallel to the fibers, the radial direction is perpendicular to the fibers and the growth rings and the tangential direction is perpendicular to the fibers and tangential to the growth rings (Green, Winandy, & Kretschmann, 2010). Accordingly, if date palm rachis is to be defined as an orthotropic material, the properties in the tangential and radial directions are identical due to the lack of growth rings in Date Palm Rachis, as illustrated in Figure 14 (Mansour, Elmously, & Darwish, 2017).

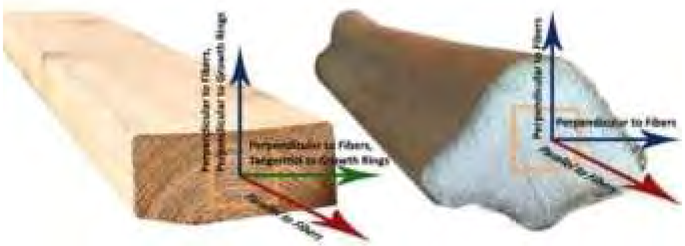

Figure 14. Axes of material in Timber and Date Palm Rachis (Yasser et al., 2017)

The considered properties to be measured are: Tension Stress, Longitudinal Modulus of Elasticity, Radial/Tangential Modulus of Elasticity, Longitudinal-Radial/Tangential Shear Modulus. These properties were considered according to the required properties for structural analysis for orthotropic materials in SAP2000; the most widely used software for structural analysis. The rest of the properties are to be measured in the upcoming papers.

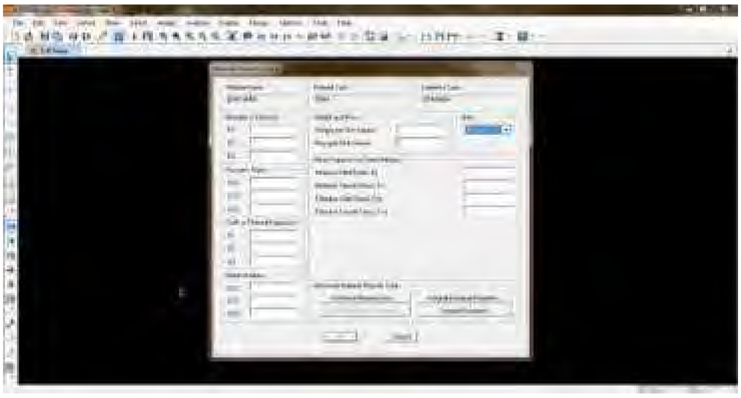

Figure 15. Material Property interface in SAP2000 (Author's own, n.d.)

3. Discussion

The following properties were measured for "*Baladi*" species of date palm trees in Minya governorate along the Nile Valley in the metalloids Laboratory and Polymers Laboratory in the Faculty of Engineering, Ain Shams University. The properties are carried out on the middle portion of the rachis using DIN EN 408-2004 standards with 12% moisture content.

3.1. Tensile Stress

The tensile stress was measured through the Stress-Strain Curve of Tension. The yield stress is the stress at the end of the elastic zone, while the ultimate stress is the highest stress before the failure. The ultimate tensile stress has been measured for the whole date palm rachis from three species in Egypt and showed a mean value of 80 MPa. New measurement took place in the Polymers Labs in the Faculty of Engineering using precast Epoxy grips. The experiment was evaluated on three specimens to validate the results according to previous studies. The nominal dimensions of the specimens are illustrated in Figure 16. Each specimen was inserted in the ends in hollow PVC tubes and with a length of 10 cm and epoxy SIKADUR was poured inside, then the tubes were sewn off using lathe. The testing was made on 3 samples of *Baladi* Species (Figure 17), by Lloyd 300k capacity testing machine, with a rate of 2 mm/min. according to DIN EN 408-2004 (Figure 18).

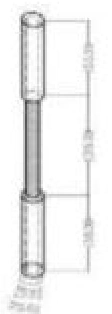

Figure 16. Specimen Dimension (Author's own, n.d.)

The failure of each specimen was marked when the first crack in the epoxy appeared, as the crack happens due to the unique behavior of the palm rachis under tension, where the fibers tend to loosen, leading to the cracking of the brittle epoxy around (Figure 19). This can be noticed after the epoxy could be easily removed, revealing longitudinal cracks between the loose fibers in the specimen underneath, which indicates the failure of the specimen (Figure 20).

The Stress-Strain curves of the three specimens showed considerable variations, which was expected as the specimen were not taken from the same rachis (Figure 21). The Stress-Strain curves showed the following:

- It was found to be relatively close to that of white spruce in terms of the acute inclination of the curve in the elastic zone.
- The Minimum Yield Stress was found to be 40 N/mm^2.
- The mean of Minimum Tensile stress was found to be 65 N/mm^2.
- The mean of Yield Stress was found to be 55N/mm^2.
- The mean of the Tensile Stress was found to be 75 N/mm^2.

These values were considerably close to those of previous research (Elmously, 2001).

Figure 17. The tension specimens before testing (Author's own, n.d.)

Figure 18. The tension procedures in the testing machine (Author's own, n.d.)

Figure 19. Longitudinal cracks in Epoxy and Specimen (Author's own, n.d.)

Figure 20. Zoom in on the longitudinal cracks under the Epoxy (Author's own, n.d.)

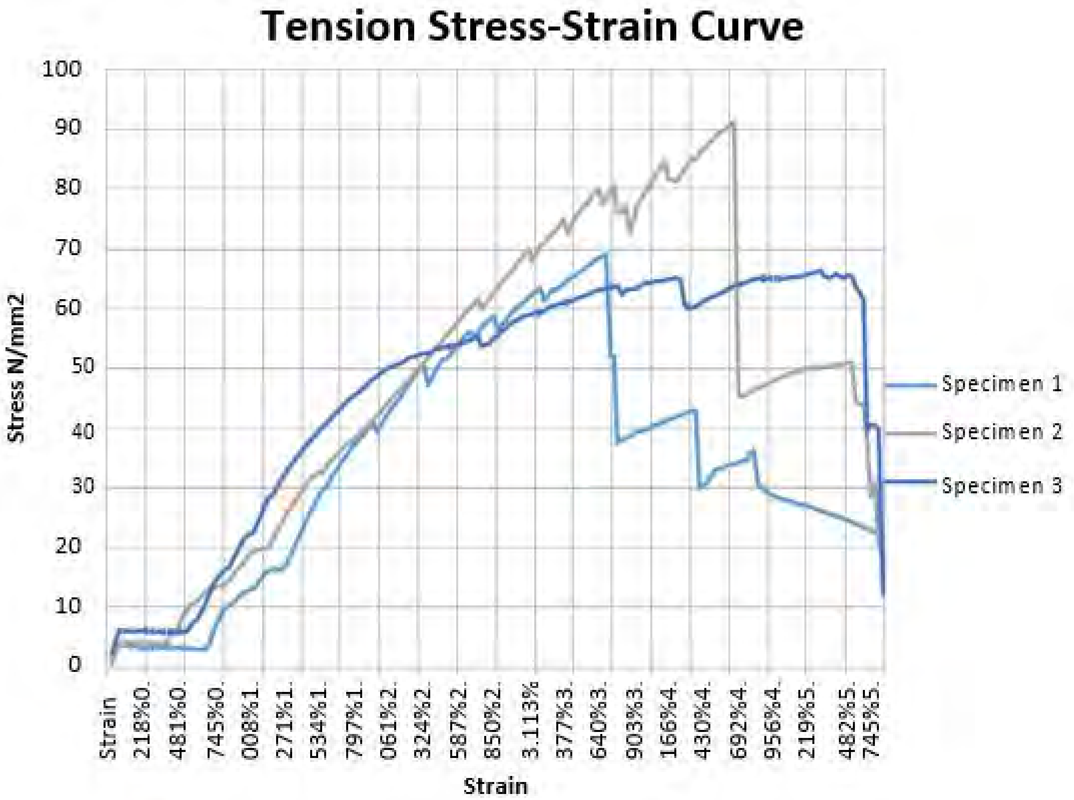

Figure 21. Tensile Stress-Strain Curves of the 3 specimens

3.2. Longitudinal Modulus of Elasticity

The longitudinal modulus of elasticity is often obtained by bending for rough and natural materials like bamboo and palm rachis, as the preparation procedures for tension were found to be complicated as shown in the previous section. The longitudinal modulus of elasticity included an effect of shear deflection. Therefore, the Shear-Free Elasticity Modulus is calculated by increasing the Apparent Modulus of Elasticity by 10% (Green et al., 2010).

The measurements were made for 5 specimens that were dried for 12% moisture content or less. The bending measurement was over a span of 360 mm in relative to the specimen dimension, as illustrated in Figure 22, according to DIN EN 408-2004 by Lloyd 300k capacity testing machine, with a rate of 2 mm/min (Figure 23).

Figure 22. Dimensions of the bending specimen (Author's own, n.d.)

The failure of each specimen was automatically identified by the machine when no more resistance was received. The failure of the specimen had a sharp breaking point, with longitudinal cracking as the fibers loosen from the load once it exceeded the ultimate limits of the material (Figures 24 and 25).

According to DIN EN 408-2004, the apparent modulus of elasticity is calculated using load, displacement and the moment of inertia, by the following equation:

$$E_{app} = \frac{l_i^3 (F_2 - F_1)}{48I\ (W_2 - W_1)} \tag{1}$$

Where

- F_2-F_1 is an increment of load on the straight line portion of the load-deformation curve in Newtons.
- W_2-W_1 is the increment of deformation corresponding to F2-F1 in millimeters.
- l_i is the span between supporters in millimeters.
- I is the second moment of area, in millimeters to the fourth power.

Therefore, the testing results needed are Load-Machine Extension curves (Figure 26).

Thus, according to equation 1, the mean E_{app} of the 5 specimen was found to be 9532.5 N/mm^2, and by excluding the shear effect, the actual *El* is 10287 N/mm^2. This result was considerably close to those of previous research (Elmously, 2001).

Figure 23. The Bending Procedures in the testing machineb (Author's own, n.d.)

Figure 24. The Failure Pattern in the specimens (Author's own, n.d.)

Figure 25. The longitudinal cracking in a specimen (Author's own, n.d.)

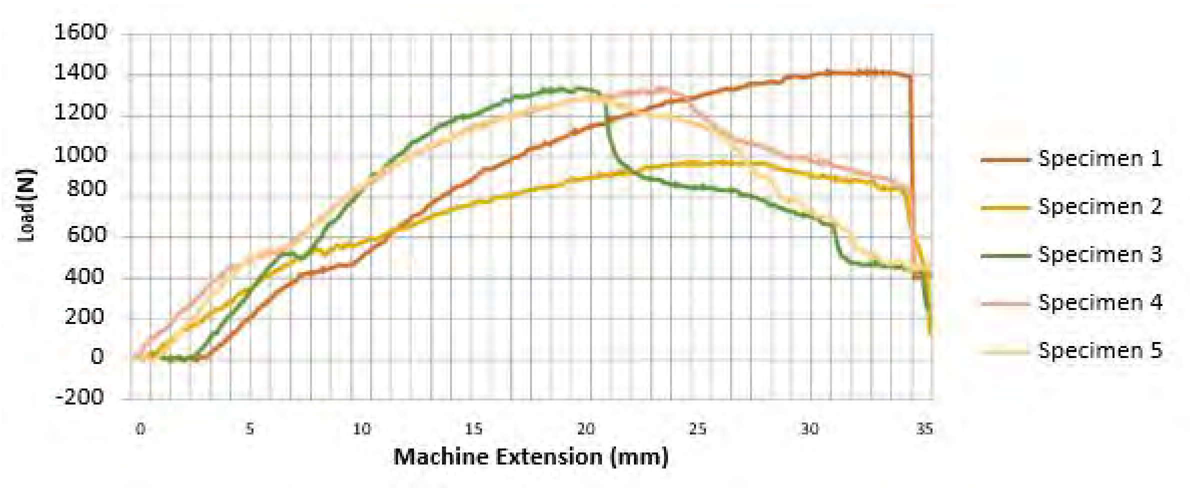

Figure 26. Load-Extension Curves of the 5 specimen in theApparent Modulus of Elasticity (Authors)

3.3. Radial/TangentialModulus of Elasticity E $_{r/t}$

Due to the natural long shape of palm rachis that is unable to be formed into specimen that can be tested for tension or bending perpendicular to fibers, a compression test was used to calculate the radial/tangential modulus of elasticity that is perpendicular to fibers. The palm rachis were dried to 12% moisture content, shaped into 5 specimens and tested by Lloyd 50k capacity machine, with a rate of 1.5 mm/min (Figures 27 to 29).

Figure 27. Dimensions of the specimen of compression (Author's own, n.d.)

Figure 28. The Compression procedures in the testing machine (Author's own, n.d.)

The failure of each specimen was automatically identified by the machine when no more resistance was received. The specimens suffered buckling under compression, in addition, cracks were originated between the fibers that tend to loosen from the load once it exceeded the ultimate limits of the material. According to DIN-EN 408-2004, the compression modulus of Elasticity is calculated using load, displacement and the dimensions, by the following equation:

$$E_c = \frac{h_o(F_2 - F_1)}{bl(w_2 - w_1)} \tag{2}$$

Figure 29. The failure patterns of the compression specimens (Author's own, n.d.)

Where

- F_2-$F_1$is an increment of load on the straight line portion of the load-deformation curve in Newtons.
- W_2-W_1 is the increment of deformation corresponding to F_2-F_1 in millimeters.
- h_0 is the height of the sample.
- b is the width of the cross section of the sample.
- l is the thickness of the cross section sample.

Therefore, the testing results needed are Load-Machine Extension curves, which are illustrated in Figure 30.

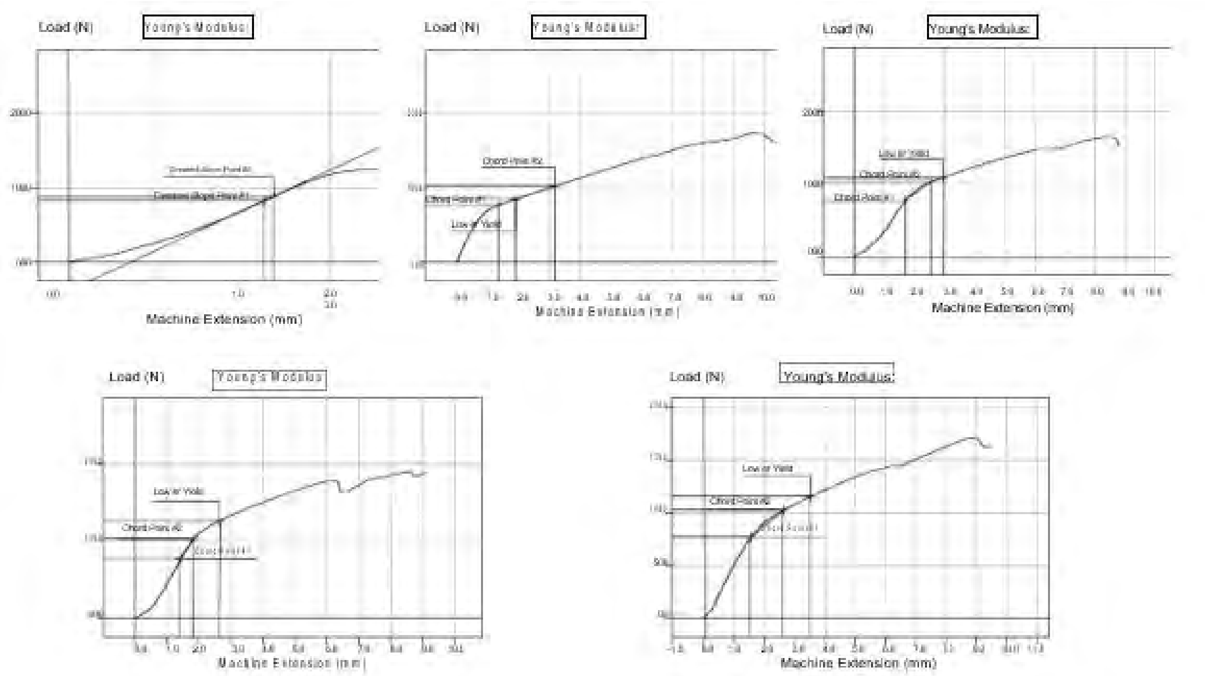

Figure 30. Load-Machine Extension Curves of the 5 specimenin the compressive Modulus of Elasticity (Author's own, n.d.)

3.4. Longitudinal-Radial/TangentialShear Modulus $G_{lr/t}$

No previous researches assigned shear modulus of Date palm rachis. The Shear Modulus induced from Bending measures the ratio of the stress and strain resulting from the shear deflection. The resultant Shear Modulus is based on shear strain parallel to fibers and shear stress perpendicular to fibers. DIN EN 408-2004 contains a sector that is specified to measure the shear modulus through the Variable Span method; where the apparent modulus of elasticity is measured using bending testing over 3 variable spans that are chosen based on the rules of DIN EN 408-2004, then the sum of the reciprocal of the values of the 3 spans is used in the following equation:

$$G = \frac{K_G}{K_1},\ K_1 = \frac{\triangle \frac{1}{E_{app}}}{\triangle \left(\frac{h}{l}\right)^2} \tag{3}$$

Where K_G is 1.2 for rectangular or square cross sections, and *K1* is the slope of the graph of the reciprocal of the 3 spans E_{app} and the squared ratio of sample height to span between supports. The testing procedure is illustrated in Figures 31 through 35.

Figure 31. Dimensions of the Bending specimen (Author's own, n.d.)

Figure 32. The Bending Procedures in the testing machine for span 220 mm (Author's own, n.d.)

Figure 33. The Bending Procedures in the testing machine for span 280 mm (Author's own, n.d.)

The failure patterns were found to be more acute as the span increased. The failure pattern in the specimens of the 220 mm span testing was a mild deflection, while deep longitudinal cracks and stronger deflection occurred to the specimens of the 280 mm span testing. However, the specimens of the 400 mm span testing suffered sharp breakage points at the middle of each specimen. The results of the tests are illustrated in Figures 36-39.

The final results of the testing showed that $Gl_{r/t}$ was 109.2 MPa according to equation 3, which lies within the 50-150 MPa limits of Shear Modulus of Softwoods under the same moisture content (Green et al., 2010).

Figure 34. The Bending Procedures in the testing machine for span 400 mm (Author's own, n.d.)

Figure 35. The failure patterns of the Variable Span Method specimens (Author's own, n.d.)

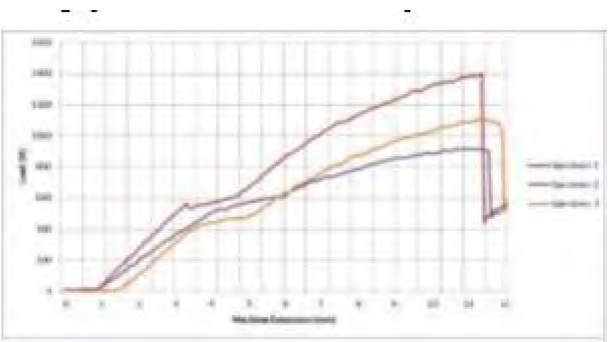

Figure 36. Graphs of the apparent Modulus of Elasticity of span 220 mm (Author's own, n.d.)

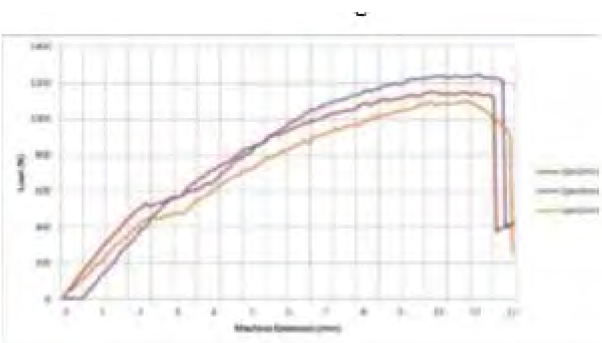

Figure 37. Graphs of the apparent Modulus of Elasticity of span 280 mm (Author's own, n.d.)

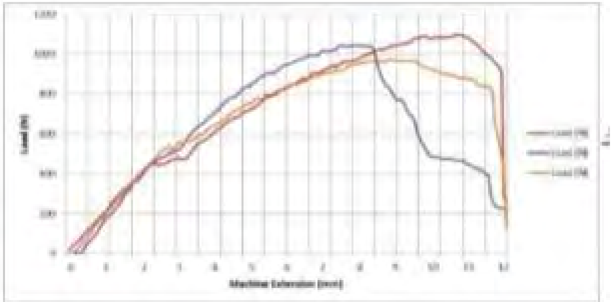

Figure 38. Graphs of the apparent Modulus of Elasticity of span 280 mm (Author's own, n.d.)

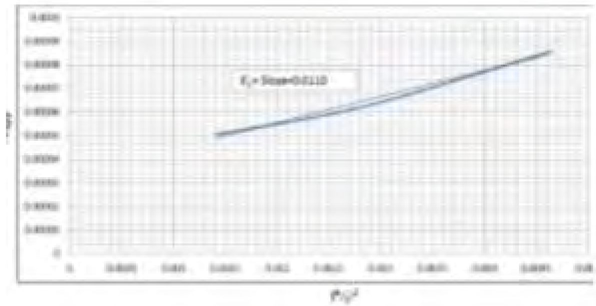

Figure 39. The slope of K1 (Author's own, n.d.)

3.5. Calculation of Radial-Tangential Shear Modulus G$_{rt}$

As noticed from the previous testing, Shear modulus was entirely based on the measurement of longitudinal apparent modulus of elasticity. However, most of the previous research have not indicated how to measure the radial-tangential shear modulus that is entirely perpendicular to fibers as it can be negligible relative to the much higher values of the properties in the direction of fibers, specially for naturally long-shaped elements like Date Palm Rachis. The same applies for Poisson ratio measurements. Therefore, by assuming Poisson ratios with reference to the properties to Spruce wood as 0.30, G_{rt} can be calculated by the following equation (Racero, Nieto, & Ávila, 2015):

$$\therefore G_{RT} = 0.5\left(\frac{E_T}{1+\mu_{RT}}\right) = 0.5\left(\frac{105.45}{1+0.30}\right) = 40.55\,N/mm^2 \tag{4}$$

4. Conclusion

Date palm rachis has been used for traditional construction using the pure instinct and experience of the rural builders in the rural areas in Egypt and the Middle East. However, the pre-construction structural analysis could help to make the date palm rachis-based structures more resistant to unpredictable forces like winds, seismic loads and onsite behaviors. This paper introduced the closest estimations of the mechanical properties of whole date palm rachis using the available equipment in the laboratories of the Faculty of Engineering, Ain Shams University.

Although date palm rachis is considered an anisotropic material, the linear orthotropic model was used to identify the axes of the material where the properties are to be measured. It was found that the properties of date palm rachis in the linear orthotropic model are supposed to be identical in the radial and tangential directions. The proposed date palm rachis properties are summarized in Table 2.

These properties cover most of the required properties to define Date Palm Rachis into structural analysis software like SAP2000. These findings prove that Date Palm Rachis is competitive to imported wood species in Egypt. This opens the door for further researches to structurally evaluate the potentials of Date Palm Rachis as a versatile building material that can be used as a substitute to expensive imported wood in Egypt.

Table 2. The mechanical properties of date palm rachis baladi species

Mechanical Property	Property Symbol in SAP2000	Value (N/mmm)
Minimum Yield Stress	F_y	40
Minimum Tensile Stress	F_u	65
Effective Yield Stress	F_{ye}	55
Effective Tensile Stress	F_{ue}	75
Longitudinal Modulus of Elasticity E_l	E_1	10287
Radial & Tangential Modulus of Elasticity Er, E_t	E_2, E_3	105.45
Longitudinal-Tangential Shear Modulus G_{lt},	G_{12}, G_{13}	109.2
Longitudinal-Radial Shear Modulus *Glr*		
Radial-Tangential Shear Modulus *Grt*	G_{23}	40.55

5. Acknowledgments

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