Development of the Structural Uses of Date Palm Rachis for Cheap Wide Span Construction for Rural Communities in the Middle East

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Abstract. Date palm rachis is one of the most abundant agricultural wastes in Egypt that is being used traditionally in making furniture and sheathing by rural communities in Egypt. This familiarity attracted previous researchers to develop the use of date palm rachis for cheap construction in order to introduce palm rachis as a local building material which contributes to empowering rural communities in Egypt. Most of the wide-span date palm rachis based previous studies lacked simplicity and flexibility that is required to encourage communities to exploit the structural abilities of palm rachis. This paper aims to exploit the philosophy and potentials of palm rachis by combining traditional concepts with modern techniques in order to increase the available covered spans, which would promote the potentials of Date Palm Rachis. This aim is served by introducing a new concept of using palm rachis for simple wide span construction utilizing arched truss Form-Active structural systems. This primary design is built in an experimental scaled model to investigate the durability and details of the suggested system. The findings encourage researchers and local builders to investigate the potentials of date palm rachis as a cheap and local building material for rural communities in Egypt.

1. Introduction
The demand for shaded areas is increasing rapidly under the circumstances of Global Warming that make activities in exposed areas almost impossible. However, the choice of conventional steel trusses is not always available for poor rural communities under the circumstances of the high inflation rate, which increases the cost of the expensive imported materials. Therefore, natural local materials are now the new trend to be used as a substitute for the expensive conventional building materials [1]. Natural local materials enjoy the privilege that most rural communities around the world have a strong technical heritage in using them in a wide range of inherited techniques, from making furniture and ornaments, to building their own houses [1]. This heritage qualifies natural local materials such as timber and bamboo to replace conventional shades and steel trusses that are used to cover wide spans to host flexible activities such as markets and community centres for poor rural communities [1].

Date Palm Rachis ranks the first among the amounts of the annual pruning residues of Date Palm Trees in Egypt. This gave Date Palm Rachis a huge part of the craftwork such as ornaments, chairs, fences and simple sheathing in rural communities in the western oases and Nile Delta as illustrated in Figures 1 and 2 [3].
This undeniable familiarity between Date Palm Rachis and the rural communities in the Middle East encouraged several previous researches to investigate the potentials of Date Palm Rachis as durable and versatile independent structural elements [2].

2. Techniques of utilizing date palm rachis in construction

2.1 Bundling technique
Collecting thin elements into bundles has been a common way to store and move agricultural residues. Moreover, shaping those bundles with ropes within a fixed distance along the bundles adds stability and durability to the bundles, that they can be used for construction instead of depending entirely on wooden columns. This technique created the vault in Mudhif in Iraq as illustrated in Figure 3 [4]. Reeds are shaped into 70cm diameter bundles that are planted in the soil on each side of the proposed vault, and then the bundles are bent in order to tie the ends of every bundle with its counterpart on the other side [5]. The bundle purlins are assembled with robes every four inches, and then they are forced through the compressed arches using friction to add stability to the structure and unite the arches into one structure, as illustrated in Figure 4 [5]. The span of the result vault is about 6-13 m, and the vault itself is fast and easy to erect and move, as it depends only on the reeds bundles [4].

This technique inspired [6] to try the same system using Date Palm Rachis. Unlike reeds, Date Palm Rachis is not hollow and has higher density, which makes bundles with 70cm diameter made of Date Palm Rachis very heavy to erect. Therefore, Date Palm Rachis elements were shaped to make long bundles of 20 cm diameter. One end of each bundle was planted along one side of the proposed vault, and then each bundle is bent where the other end is to be planted along the other side to form an arch, as illustrated in Figure 5. However, palm trunks were added at distance 3.25 m along every arch to support the arches and decrease the deformation as illustrated in Figure 6. Hence, the actual span decreased to only 3.25m, which is less than what is needed to cover flexible and various activities [6].
2.2 Truss and space truss

Lately, [7] began the first attempt to use Date Palm Rachis for wide span construction using Space truss structural system without depending on palm trunks or wooden columns. A geodesic dome was designed and analysed to cover a diameter of 13m. Due to the shortage of resources, Ref. [7] built an experimental space truss to cover an area of 3x3 m to test the joinery that was proposed in the geodesic dome.

The whole date palm rachis elements were shaped to 10x10mm strips [7]. The strips are gathered to make 1m bundled squared members of cross section 10cm² [7]. The space truss was a 4-faced triangular truss system with its diagonal length equals to one meter [7]. The joints of the structure were designed as a steel plate with 2 U-shaped high strength bolts holding down the members to the steel plate, as illustrated in Figure 7 [7].

However, the proposed structure suffers of the high cost of the joinery due to the high complexity of the non-standard joints. In addition, the difference in the coefficient of expansion between metal and Date Palm Rachis decreases the durability and stability of the joints.

3. Objectives and methodology

Based on the previous literature review, it can be concluded that most of the previous researches utilized Date Palm Rachis to act as elements among a specific structural system, regardless of the nature of the material or the traditional techniques of building using the material.

This paper aims to introduce a new understanding of the nature of Date Palm Rachis, in order to employ this understanding to propose a structural concept that is based on a fusion between the traditional techniques and the works of the previous researchers. This structural concept should be characterized with the following:

- Cheap components: consists mostly of whole Date Palm Rachis with minimum dependence on manufacturing.
- Simple joints: utilizes minimalist connections that depend on friction between the elements with the minimum use of ropes or intermediate elements.
The objectives are served by the following methodology:

- Studying the nature of the material through personal experience building a simple shade.
- Proposing the structural technique via analysis and a scaled physical model in order to study the practicality of the details corresponding with the nature of the material. This defines the limitations of the proposed concept for further researches.

4. Discussion

4.1 Nature of date palm rachis

Date Palm Rachis, illustrated in Figures 8 and 9, ranks the first in the amount of the pruning residues of Date Palm Trees Phoenix Dactylifera in Egypt, with the annual rate of 105 ton/year, which equals approximately 30% of the total annual amounts [8]. Each mature Palm tree produces 10 to 26 rachises annually with total number that ranges from 100 to 125, with only half of them photosynthetic-active while the rest are required to prune [9]. Each date bunch is carried by 8 rachises, where each rachis is naturally curved to support the weight of 1-1.5 kg. This weight gives Date Palm Rachis its natural high strength at bending, where the value of the Modulus of Elasticity of bending is approximately 102 N/mm² [10]. Depending on the age, the surrounding environment and species, the length of the members, which vary between 3-6m [9].

![Figure 8. Anatomy of Date Palm Leaf [9].](image1)

![Figure 9. Dried and leafless Date Palm Rachis.](image2)

The density of the fiber bundles in the rachis peaks right at the periphery layer which conceals the fibers inside and decreases at the core zone [11]. Previous measurements showed that the density in the periphery layer equals 1.14gm/cm³, with Young Modulus of 15.4 kN/mm², while the density decreases in the core zone to be 0.8gm/cm³, with Young's Modulus of 4.9 kN/mm² [8]. Most of the traditional techniques use whole rachises to make use of its high strength and high resistance to humidity, dryness and direct sunlight [2].

4.2 Structural concept for date palm rachis

4.2.1 Structural deformation of date palm rachis. The Bundling technique was used by the authors and a group of local crate makers to build a 2x3 shade in less than 4 hours in a Qayat village in Menya Governorate in Upper Egypt. The technique was found to be very simple, cheap and fast. However, the shade suffered major deflection in the 5cm diameter beams and buckling in the 10cm diameter columns over the small spans of the shade, in addition to the entire dependence on ropes for the joints, which decreased the overall stability and increased the threat of failure under the force of wind. It can also be realized that the natural bent shape of Date Palm Rachis contradicts post-beam structural concept, which causes the instantaneous deformation and buckling of the structure, as illustrated in Figure 10. Moreover, the perpendicular connection of the bundles depended entirely on ropes to hold the bundles which do not intersect at any point, but rather overlap within the space where the ropes are tied repeatedly to secure the connections.
Figure 10. Deformations in the shade in Qayat.

In addition, the connections are clearly unstable and ineffective for homogenous load distribution. This obvious deformation did not occur in the bundles shaped as arches that were discussed previously by [6]. The arches fitted the natural curved shape of the bundles, decreasing the straight members that face the threat of buckling in the structure. In addition, the natural mild curvature of the bundles made the formed arches consistent and spontaneous with homogeneous overlaps that are fastened using ropes over adequate distances, which required less complicated connections along the length of the arches. Hence, the structural behaviour of Date Palm Rachis is better distributed within systems that respect their natural curved shape.

4.2.2 Compressive form active elements: concept of arches. It is clear that the simplicity and workability of the arched bundles concept are higher than those of the space truss systems. However, the Date Palm Rachis space truss in the geodesic dome theoretically provided wider spans without depending on intermediate columns [6]. Therefore, the arched bundles concept requires improvement to increase the covered span while sustaining maximum practicality and simple connections. The main concept of arches is to turn all the internal forces and bending moment to compression, as much as possible, unlike a planar slab which contains internal forces of tension and compression from moments [12]. Single span arches without moment-resistant special bases with coplanar supports and uniform load distribution, conform all the internal forces to compression, following a parabolic shape. Parabolic arches are more significant when using building materials that are subject naturally to bending and shear, than when using stiffer materials such as wood, steel and reinforced concrete [12].

4.2.3 Semi form-active structures. In the Mudhif structure, the 70 cm diameter parabolic arches were used to cover the span of 13m [4]. As previously stated, Ref. [6] added intermediate columns to replace the large cross section area. Therefore, the idea of semi Form-Active Structures emerges. A Semi Form-Active structure is used when it is needed to cover a long span using more efficient members than post-beam structures while using light members with less weight without using fabrics or tent like fully form-active structures [13]. This can be realized in Bridge engineering which utilizes more efficient shapes in cross-sections and longitudinal profiles instead of simple Post-Beam structures for long spans [13].

4.2.4 Proposed structure: arched space truss. The use of parabolic arches in the previous examples confirms the significance of parabolic arches in shaping the chords of the bridge space trusses. Hence, using parabolic arches that contain only compression will exert compression on any purlins or additional members that are inserted perpendicularly into the arches. Thus, the threat of disassembly due to tension is minimized, where friction is theoretically large enough to hold the members together without the dependence on complicated steel connection like in the space truss concept, or using robes to wrap the joint repeatedly like in the local shade experiment discussed previously. Accordingly, arched space trusses solve the challenges of covering long spans while remaining light for shades. The proposed structure is triangular arched space truss, as the most simple space truss configuration [14], where the three parabolic chords are assumed to be made of bundles of vertically dried Date Palm Rachis with a diameter of 20cm as in [6]. The bracings are assumed to be regular
gable to simplify the structure, with bundles of horizontally dried Date Palm Rachis with a diameter of 10cm diameter similar to the columns in the Qayat shade that is discussed previously (Figure 10). The basic span chosen is 8m, and the height of the chords depends on the parabolic equation. The bundles are stacked with ropes on moderate intervals along the bundles. The connections depend on the friction of the compression of inserting the endings of the bracing members inside the continuous bundles of the parabolic truss chords. The proposed design is illustrated in the Figures 11 and 12.

Figure 11. Plan of the proposed system.  Figure 12. Perspective of the proposed structure.

4.3 Procedures of the physical model

Physical models help to address the consecutive challenges of the construction process. A scaled physical model was built to study the details of the structure system in terms of the bundles assembly, bracings and joints. Dried whole rachises were sliced to smaller strips, where every strip imitates 4 actual rachises. The physical model was constructed with a scale of 1:20 due to the limitation of available space and time. A short brief about this model was published in a previous paper by the authors [15]. Following are the details and analysis of the model:

4.3.1 Dimensions of the structure. The main chords were assumed to be 20cm diameter according to [6], the intermediate bracings were assumed to be 10cm diameter according to the Qayat shade that was discussed previously in Figure 10. The span was designed to be 8m with parabolic chords.

4.3.2 Shaping the bundles. Firstly, the bundles were assembled to make the arches. The assumed cross section was made for the entire length of each bundle which is 15m, where each bundle consisted of three overlapping groups to imitate the real length of the rachises which is limited to 6m. However, the bundles upon manual bending were fractured in the middle where the curvature is the most acute along the arches, as illustrated in Figure 13. Therefore, the bundles were modified to be more flexible at bending. The cross section of the middle group was reduced as it can be assumed that the compression loads of the own weight in the peak of the parabolic arches are the least. Those new bundles were flexible at bending and no fracture occurred, as illustrated in Figure 14.

A plywood base was used and drilled at the bases of the arches to create the target span, and by adjusting the length of the arch to be planted; the parabolic shape could be achieved. The bundles were bent and inserted into the drilled holes. In addition, an inclined post was used to assess the versatility of the system. That inclined post was held only by the friction between the three arches that share the same bases, as illustrated in Figure 15.

Figure 13. Fractured full cross section arch.  Figure 14. The decreased middle cross section arch.  Figure 15. The structure before bracings.
4.3.3 Inserting the bracings and purlins. The bracings at the bottom of the arches were forced into the bundles, and the bracings at the peaks of the arches were rested on the arches, and then the rest of bundles that were subtracted from the middle group were put and tied tightly to enclose the inserted bracing using the pressure of friction in the parabolic bundles. In addition, the purlins between the two arched space trusses were also inserted through the bundles, as illustrated in Figure 16. Those purlins were assumed to only carry the loads of the wind and their own weight, as the cover is out of the scope of the research. After completion, the physical model was found to be stable and the bracings and the chords were well attached.

![Figure 16. The physical model after completion.](image)

4.4 Analysis of the physical model
Under the available conditions, the scale of physical model was insufficient to undergo physical load testing. However, it was sufficient to understand the behaviour of the elements of the structure. The inspection of the stability of the physical model during the building process proved that the core strength of this system depends on the bracings that unite the 3 arched bundles to act as a triangular arched space truss. The single arches only stood up due to the fixed foundation which resisted the thrust occurring at the ends of the arches. However, the least pressure would break the reduced middle section of the bundles.

On the other hand, the unified action of the arches increased the stability of the structure and reinforced the resistance to deformation under pressure applied by hand, especially when compared to the stability of the structure before inserting the bracings. Moreover, tying the subtracted elements of the middle section of the arches over the ends of the bracings exposed the bracing joints to the compression inside the parabolic arches, which ensured the decrease of the threat of failure under applied pressures by hand on all the joints, especially in the lower parts of the arches, where the compression loads are the maximum. However, the purlins between the two arched space trusses suffered deformations because of their low weight and the lack of connections to fix the purlins along the spacing between the 2 space trusses. Moreover, the long beams on the side suffered minor deflection over the spacing of 6m.

5. Conclusion
Date Palm Rachis is a natural agricultural pruning residue that is abundant in Egypt and the Middle East. Date Palm Rachis enjoys familiarity in the rural communities as a material for hand crafts and simple sheathing for shades and simple structures. This paper analysed traditional techniques of utilizing Date Palm Rachis and recent researches that exploit the potentials of Date Palm Rachis for modern structure systems. In order to introduce the fusion concept that merges the simplicity of the traditional techniques and the practicality and structural integrity of the modern systems, the paper proposed arched space truss, where the form active parabolic arches offer compressive friction that sustain stable connections between the arched chords and the bracings without foreign metal joints that were used in the previous Date Palm Rachis trusses.
A physical scaled model was constructed to study the full behaviour of the structure. The scaled physical model proved to be durable and structurally stable and the threat of disassembly of the bracings were minimized. However, the intermediate purlins between the two arched space trusses were found to need more improvement in order to reduce their deformation to carry the weight of the sheathing. In addition, the side post and beam shades suffered deformations, which confirm that form active systems are more suitable than post and beam structures for Date Palm Rachis construction.

The results of this paper call for additional studies to build the model in adequate scales for physical testing of the structural performance. Moreover, additional studies are needed to define the most suitable light covering technique and the fixation of the covering to the intermediate purlins. Also, natural builders and social workers are invited to study the uses of the structure in order to be introduced to the rural communities as fast, simple and cheap shades that can be built for rural communities in Egypt and the Middle East.

6. References
[1] Kennedy J 2004 Building Without Borders: Sustainable Construction for the Global Village, (Ontario: New Society Publishers) pp30-45
[2] Elmously H 2001 The Industrial Use of The Date Palm Residues An Eloquent Example Of Sustainable Development Proc. 2nd International Conference on Date Palms (Cairo), (Dubai: United Arab Emirates University) pp 866-886
[3] Ahmed R M 2014 Lessons Learnt from the Vernacular Architecture of Bedouins in Siwa Oasis, Egypt Proc. The 31st Int. Sym. on Automation and Robotics in Const. and Mining (London: ISARC).
[4] Almssad A and Almusaed, A 2015 Building materials in eco-energy houses from Iraq and Iran, Case Studies. in Const. Mat. Ed 2 Grantham M, (Amsterdam: Elsevier) pp42-54.
[5] Ochsenschlager E L 2004 Iraq's Marsh Arabs in the Garden of Eden. (Philadelphia: University of Pennsylvania Museum of Archaeology and Anthropology)
[6] Piesik S 2012 Arish: Palm-Leaf Architecture Ed 2 (London: Thames & Hudson.) pp60-127
[7] Hassan N 2001 Use of Local Raw Materials in Low Cost Roofing Ph.D Institute of Environmental Studies & Research Ain Shams University Cairo Egypt
[8] ElMously H 2005 The Palm Fibers for the Reinforcement of Polymer Composites: Prospects and Challenges Proc. 1st Ain Shams Int. Conf. on Enviro. Eng. (Cairo) vol 1 (Cairo: Ain Shams University) p 14.
[9] Zaid A and De Wet P 1999 FAO plant production and protection papers, Chapter I pp.1-28 http://www.fao.org/docrep/006/y4360e/y4360e05.htm, last accessed Aug.2017
[10] Darwish E A, Mansour Y, Elmously H 2017 Date Palm Rachis as a local and renewable structural material for rural communities in Egypt, Al Azhar's 14th International Conference on: Engineering, Architecture and Technology (Cairo), In press.
[11] Megahed M, and Elmously H 1995 Anatomical Structure of Date Palm Leave's Midrib And Its Variation Across And Along The Midrib IUFRO XX 191World Congress (Tampere)
[12] Ambrose J and Tripney P 2012 Building Structures Ed 3 (London: John Wiley & Sons) pp60-65.
[13] Macdonald A 2001 Structure and Architecture Ed 2 (Oxford: Reed Educational and Professional Publishing) pp110-125.
[14] Lan T 2005 Space Frame Structures, in Handbook for Structural Engineering, Ed 2 W. Chen, (Tokyo: CRC Press) pp 24-50
[15] Mansour Y, Darwish E A and Elmously H 2017 Utilizing Date Palm Rachis for Flexible and Eco-friendly Construction in Egypt, Proc. World Sustainable Built Environment (Hong Kong) vol 1 (Hong Kong: HKGBC) pp 2824-33.