Experimental study on mechanical properties of reed stalk

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Abstract. Reed is a kind of important natural resources. The inherent mechanical properties of reed stalk are the basis for development of its production equipment. As the research on the basic mechanical properties of reed stalk is still in blank both at home and abroad, this paper makes the compression, tensile, and bending experiments respectively on the bottom reed stalk in the harvest time with an electronic universal testing machine, obtains the corresponding stress-strain curves under the compression, tensile, and bending loads, and confirms that the mean compression strength is 2.69 MPa, the mean compression elasticity modulus is 75.52 MPa, the mean tensile strength is 16.45 MPa, the tensile elasticity modulus is 433.19 MPa, the mean bending strength is 2.15 MPa, and the mean fracture deflection is 5.54 mm. The experimental results may provide a reference for the development and parameter optimization of the reed production equipment.

1. Introduction

Reed is a perennial gramineous plant with strong adaptability and resistance, as an important kind of natural resources [1,2] that spreads around the world. Due to the tough material and high fiber content, it is not only a high-quality paper making raw material but also a superior environmental protection material widely used in the paper making industry, the construction industry, and other industries [3,4]. In China where the forest resources are relatively rare, reed has been preferred to wood and plays a vital role in the national economy. It is hailed as the “Second Forest” [5].

As reed is tall and its bottom stalk is hard, its harvest, mostly dependent on the traditional manual harvest due to poor machinery, is a major challenge in the production process all the time. Compared to manual harvest which, high in labor intensity and cost but low in efficiency, goes against the reed industrialization development, it is significant to enforce mechanized harvest which can raise labor productivity, lower production cost, guarantee the material supply of the paper making industry, and improve the utilization ratio of such a resource.

By conducting an experimental study on the mechanical properties of reed stalk and acquiring the parameters such as compression strength, tensile strength, bending strength, and elasticity modulus, we may provide not only a theoretical reference and basic technical parameters for the selection of the cutting power, cutter type, and cutting ways of the reed harvester and the subsequent procedures such as packaging and smashing but also a basis for the structural design of the reed production equipment. But through literature search, it is found that the research at home and abroad on the reed production equipment simply focuses on the structural design of the major components of reed harvester [1,6-9], and no relevant research on the mechanical properties of reed stalk has been reported. Therefore, in order to provide a reference for development and parameter optimization of the reed production
equipment, this paper intends to carry out an experimental study on the mechanical properties of reed stalk and gain the parameters of the bottom reed stalk in the harvest time.

2. Experimental materials, equipment, and methods

2.1. Experimental materials

2.1.1. Material collection. We collected the experimental materials in the wild reed lands located at High and New Tech Development Zone, Wuxi on November 3, 2017. See figure 1 for the reeds. They were all 3~5 m high and 12~16 mm wide in bottom diameter. We selected those straight from top to bottom and about 14mm wide in bottom diameter without pests and damages randomly as the experimental materials. We cut off the reeds at the bottom, making sure their remaining height was 200 mm, sealed them in plastic bags, and finished the experiments within 72 hours.

![Figure 1. Reeds used for experimental materials.](image)

2.1.2. Specimen preparation. As this paper intends to study the compression, tensile and bending properties of reed stalk in the harvest time, we prepared the compression, tensile, and bending specimens respectively.

See figure 2(a) for the compression specimen. \( D_x, k, \) and \( h \) were the external diameter, wall thickness, and height of the specimen. \( D_1 \) and \( k \) were the actual sizes, while \( h \) was set at 30 mm (±2 mm) uniformly.

We prepared the tensile specimens by regarding the preparing methods of the specimens of bamboo wood for tensile property as the standards. See figure 2(b) for the tensile specimen. Hereinto: \( l_1, n, q, r, \) and \( t \) were the length, active length, width of the effective segment, transition radius, and thickness of the specimen. We set \( l_1 \) at 70 mm, \( n \) at 18 mm, \( q \) at 2 mm, and \( r \) at 3 mm, while \( t \) was the actual thickness of the specimen.

See figure 2(c) for the bending specimen. \( D_x, c, \) and \( l_x \) were the external diameter, wall thickness, and the length of the specimen. \( D_2 \) and \( c \) were the actual sizes, while \( l_x \) was set at 180 mm (±15 mm) uniformly.

The finished experimental specimens were shown in figure 3.
Figure 2. Structures of experimental specimens. (a) Compression specimen, (b) tensile specimen and (c) bending specimen.

Figure 3. Preparations of experimental specimens. (a) Compression specimens, (b) tensile specimens and (c) bending specimens.

2.2. Experimental equipment
We conducted the experiments basically with the WDW-10 electronic universal testing machine (with the fixtures suitable for the compression, tensile, and bending experiments) manufactured by Jinan Chuanbai Instrument & Equipment Co., Ltd. The machine has 5 KN strength, level-1 precision, 5% force accuracy, and 0.1% displacement accuracy. We also used other devices in the experiments, such as moisture content meters, art knives, and vernier calipers.

2.3. Experimental methods
We chose the experimental methods by reference to that of the physical and mechanical properties of bamboo wood [10].

During the experiments, we firstly designed an experimental scheme with the machine, measured the size parameters of the specimens with vernier calipers, recorded them into the system, and then fixed the specimens respectively with the compression, tensile, and 3-point bending fixtures. Setting the pre-tightening force for system start-up at < 1 N, the loading speed at 50 mm/min, We reset the pre-tightening force and pushed the start button, after which the system software of the machine automatically made a record of the experimental data, drew the stress-strain curves, and eliminated the invalid experiments to make sure the number of the valid experiments of each kind was 20.

See figures 4-6 for the initial clamping positions of the specimens in the compression, tensile, and bending tests.
3. Results and analysis

3.1. Results of compression experiment and analysis

See figure 7 for the stress-strain curve of reed stalk in the compression experiment. See table 1 for the data of the compression experiment.

We can see from figure 7 that the compression stress-strain curve of reed stalk can be divided into two stages: straight climb of the stress and fluctuant decline of the stress. In the initial phase of the compression process when the strain rate maintains within 6%, the stress goes up straightly as the strain increases, and the reed stalks show the property of elasticity deformation, which conforms to Hooke’s law. At the same time, the internal organizational structures of the reed stalks are compressed evenly, making the loose texture firm.

When the stress is maximized, the walls of the reed stalks begin to crack, the specimens begin to sink, and then the stress goes down sharply with fluctuation. After the stress reaches the strength set by the machine, the experiment stops automatically.
Table 1. Data of compression experiment.

| No. | External Diameter /mm | Wall Thickness /mm | Height /mm | Max Compression Force /N | Compression Strength /MPa | Elasticity Modulus /MPa |
|-----|-----------------------|--------------------|------------|--------------------------|--------------------------|------------------------|
| 1   | 11.90                 | 1.50               | 29.05      | 135.28                   | 2.76                     | 83.95                  |
| 2   | 12.32                 | 1.74               | 31.70      | 146.68                   | 2.54                     | 86.99                  |
| 3   | 13.83                 | 2.20               | 31.29      | 190.78                   | 2.37                     | 68.43                  |
| 4   | 11.98                 | 1.32               | 44.21      | 122.54                   | 2.77                     | 67.16                  |
| 5   | 13.58                 | 2.07               | 29.51      | 176.22                   | 2.35                     | 77.57                  |
| 6   | 12.58                 | 1.47               | 30.94      | 161.56                   | 3.15                     | 85.27                  |
| 7   | 12.39                 | 2.01               | 29.63      | 194.72                   | 2.97                     | 84.36                  |
| 8   | 13.70                 | 2.12               | 30.00      | 174.20                   | 2.26                     | 62.60                  |
| 9   | 12.73                 | 1.76               | 29.30      | 197.28                   | 3.25                     | 99.01                  |
| 10  | 13.38                 | 2.14               | 30.89      | 185.96                   | 2.46                     | 69.29                  |
| 11  | 12.74                 | 1.85               | 28.14      | 194.68                   | 3.08                     | 85.85                  |
| 12  | 13.28                 | 1.96               | 28.22      | 211.84                   | 3.04                     | 63.37                  |
| 13  | 12.66                 | 1.92               | 29.92      | 177.08                   | 2.73                     | 44.73                  |
| 14  | 12.58                 | 1.47               | 30.94      | 161.56                   | 3.15                     | 85.27                  |
| 15  | 12.39                 | 2.01               | 29.63      | 194.72                   | 2.97                     | 84.36                  |
| 16  | 13.70                 | 2.12               | 30.00      | 174.20                   | 2.26                     | 62.60                  |
| 17  | 12.73                 | 1.76               | 29.30      | 197.28                   | 3.25                     | 99.01                  |
| 18  | 13.38                 | 2.14               | 30.89      | 185.96                   | 2.46                     | 69.29                  |
| 19  | 12.74                 | 1.85               | 28.14      | 194.68                   | 3.08                     | 85.85                  |
| 20  | 13.28                 | 1.96               | 28.22      | 211.84                   | 3.04                     | 63.37                  |
| Mean| 12.65                 | 1.76               | 30.67      | 161.31                   | 2.69                     | 75.52                  |
| Mean Deviation| 0.61 | 0.28               | 3.35       | 28.69                    | 0.30                     | 13.60                  |

We can see from the data above that the mean external diameter is 12.65 mm, the mean wall thickness is 1.76 mm, the mean height is 30.67 mm, the mean max compression force is 161.31 N, the mean max compression strength is 2.69 MPa, and the mean elasticity modulus is 75.52 MPa.

3.2. Results of tensile experiment and analysis

See figure 8 for the stress-strain curve of reed stalk in the tensile experiment. See table 2 for the data of the tensile experiment.

Table 2. Data of tensile experiment.

| No. | Width /mm | Thickness /mm | Parallel Length /mm | Tensile Force /N | Tensile Strength /MPa | Elasticity Modulus /MPa |
|-----|-----------|---------------|---------------------|-----------------|------------------------|------------------------|
| 1   | 2.25      | 1.51          | 15.97               | 45.50           | 13.39                  | 297.14                 |
| 2   | 1.98      | 1.34          | 16.01               | 44.60           | 16.81                  | 391.47                 |
| 3   | 2.66      | 1.43          | 22.45               | 41.90           | 11.02                  | 343.63                 |
| 4   | 2.10      | 1.35          | 20.4                | 36.70           | 12.95                  | 541.87                 |
| 5   | 2.80      | 1.32          | 17.54               | 50.70           | 13.72                  | 279.25                 |
| 6   | 2.54      | 1.56          | 15.84               | 44.62           | 11.26                  | 576.73                 |
| 7   | 1.76      | 1.61          | 19.43               | 57.38           | 20.25                  | 442.83                 |
| 8   | 2.10      | 1.57          | 17.00               | 60.98           | 18.50                  | 424.33                 |
| 9   | 2.37      | 1.50          | 18.06               | 43.88           | 12.34                  | 592.93                 |
| 10  | 1.82      | 1.24          | 17.87               | 48.26           | 21.38                  | 284.69                 |
| 11  | 2.67      | 1.78          | 17.30               | 79.04           | 16.63                  | 471.71                 |
| 12  | 2.45      | 1.45          | 18.08               | 62.38           | 17.56                  | 435.92                 |
| 13  | 1.71      | 1.58          | 14.07               | 46.80           | 17.32                  | 440.59                 |
| 14  | 1.96      | 1.08          | 15.00               | 56.12           | 26.51                  | 433.56                 |
| 15  | 2.38      | 1.62          | 20.02               | 48.18           | 12.50                  | 545.59                 |
We can see from figure 8 that the tensile stress-strain curve of reed stalk can be divided into three stages: constant stress, steady climb of the stress, and sudden drop of the stress. In the first state where the strain rate maintains 0~2%, the stress remains unchanged as the strain increases. After analyzing the experimental process, we can see that it is caused by the small slips of the chunk of the machine. In the second stage, the stress rises like a semi-parabola as the strain increases, and the organizational structures of the specimens show plastic deformation under the tensile load. In the third stage where the stress is maximized, the specimens are snapped, and the stress falls to zero suddenly.

We can see from the data above that the mean tensile force is 49.87 MPa, the mean tensile strength is 16.45 MPa, and the mean elasticity modulus is 433.19 MPa.

3.3. Results of bending experiment and analysis
See figure 9 for the stress-strain curve of reed stalk in the three-point bending experiment. See table 3 for the data of the bending experiment.

We can see from figure 9 that in the initial state, the stress-strain curve is nearly linear. After analyzing the experimental process, we can see that the reed stalks show elastic deformation under the bending load but no bending failure.

When the yield stress occurs (i.e. the strain rate is around 7%), the stress goes down quickly as the strain increases, and the reed stalks are snapped under the bending load. After that, the stress goes down quickly as the strain increases and tends to be constant when the strain is about 20%.

We can see from the data above that the mean max force is 17.92 N, the mean bending strength is 2.15 MPa, and the mean fracture deflection is 433.19 MPa.
Figure 9. Bending stress-strain curve.

Table 3. Data of bending experiment.

| No. | External Diameter /mm | Wall Thickness /mm | Span /mm | Max Force /N | Bending Strength /MPa | Fracture Deflection /mm |
|-----|------------------------|--------------------|----------|--------------|-----------------------|-------------------------|
| 1   | 12.48                  | 1.64               | 90       | 16.54        | 2.37                  | 5.12                    |
| 2   | 12.17                  | 1.94               | 90       | 20.40        | 2.62                  | 5.50                    |
| 3   | 14.37                  | 1.8                | 90       | 24.00        | 2.70                  | 6.25                    |
| 4   | 14.15                  | 1.54               | 90       | 17.38        | 2.28                  | 6.10                    |
| 5   | 12.41                  | 1.61               | 90       | 15.94        | 2.34                  | 4.43                    |
| 6   | 12.08                  | 1.57               | 90       | 12.38        | 1.91                  | 4.80                    |
| 7   | 13.03                  | 1.21               | 90       | 11.00        | 1.96                  | 5.67                    |
| 8   | 12.74                  | 2.09               | 90       | 22.72        | 2.60                  | 5.64                    |
| 9   | 13.59                  | 1.86               | 90       | 16.16        | 1.92                  | 5.09                    |
| 10  | 13.60                  | 2.04               | 90       | 14.38        | 1.55                  | 6.40                    |
| 11  | 12.93                  | 1.72               | 90       | 19.66        | 2.60                  | 4.45                    |
| 12  | 14.69                  | 2.04               | 90       | 19.66        | 1.94                  | 6.81                    |
| 13  | 13.47                  | 1.69               | 90       | 16.44        | 2.10                  | 4.93                    |
| 14  | 13.81                  | 2.11               | 90       | 13.70        | 1.41                  | 6.41                    |
| 15  | 15.77                  | 1.76               | 90       | 25.42        | 2.63                  | 6.70                    |
| 16  | 14.86                  | 2.14               | 90       | 20.30        | 1.90                  | 6.47                    |
| 17  | 13.91                  | 2.25               | 90       | 16.46        | 1.60                  | 6.28                    |
| 18  | 15.32                  | 2.06               | 90       | 22.24        | 2.07                  | 4.65                    |
| 19  | 12.39                  | 2.13               | 90       | 11.8         | 1.37                  | 4.53                    |
| 20  | 11.83                  | 1.69               | 90       | 21.90        | 3.26                  | 4.17                    |
| Mean| 13.47                  | 1.84               | 90       | 17.92        | 2.15                  | 5.54                    |
| Standard Deviation | 1.13 | 0.27 | 0 | 4.16 | 0.49 | 0.88 |

4. Conclusion and discussion
Through the compression, tensile, and bending experiments of the bottom reed stalks in the harvest time, we acquire the corresponding stress-strain curves, and through the deformations of the reed stalks in the
experiments, we know the failure form and law of the reed stalks and identify compression strength, compression elasticity modulus, tensile strength, tensile elasticity modulus, bending strength, fracture deflection, and other parameters. The experimental results may provide a reference for development and parameter optimization of the reed production equipment.

This paper conducts the experiments only on the samples in a certain region. As China is vast in territory, the forms and mechanical properties of the reeds in one place and of one type differ largely from that of the reeds in other places and of other types. As this paper does not take the variation into consideration, the experimental results are not so highly representative. In the future studies, it will pay more attention to the variation and establish a database of the mechanical properties of the reeds in different places and of different types, with a view to providing a more comprehensive reference for the reed production equipment.

Acknowledgments
We greatly appreciate the careful and precise reviews by the anonymous reviewers and editors. This work was supported by This research was financially supported by the National Key R & D Program of China (2016YFD0701404) and the Agricultural Science and Technology Innovation Program of Chinese Academy of Agricultural Sciences (ASTIP, CAAS).

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