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Tensile Performance of a Novel Glue-Laminated Cornstalk Scrimber

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ABSTRACT

Glue-laminated cornstalk scrimber is a novel composite to substitute timber. This composite can be prepared in three steps: selecting flawless cornstalks, laying them parallel to grain, and gluing the scrimbers under high pressure. Compared with ordinary timber, glue-laminated cornstalk scrimber excels in the resistance to water, damping, insect, and fire. It is therefore widely recognized as novel eco-friendly and cost-effective composite with great potential in the building industry. The tensile strength of glue-laminated cornstalk scrimber mainly depends on the parallel-to-grain strength of its fibers. The mechanical performance parallel to grain directly determines that of this composite. Hence, this paper carries out experimental analysis on the Young's moduli and parallel-to-grain tensile strengths of cornstalk scrimber and glue-laminated cornstalk scrimber. The results show that the load-strain curve of glue-laminated cornstalk scrimber basically changed linearly parallel to grain, and the material exhibited stable Young's modulus and good strength; the glue-laminated cornstalk scrimber had a slightly higher tensile strength than cornstalk scrimber, and could thus replace timber as a building material.

Keywords: *cornstalks, scrimber, glulam, tensile strength, mechanical performance*

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1. INTRODUCTION

The development of green building materials is a prevailing trend in the building industry. In recent years, the building industry witnessed rapid progress in timber structure. Various timber substitutes have emerged, such as glulam and scrimber.

Many Chinese and foreign scholars have explored extensively into green building materials. For example, Sun et al. [1] compared the manufacturing techniques, modeling methods, and mechanical performances of three novel engineered timber composites. Zhao and Zhang [2] investigated the influence of sectional size on the ultimate compressive strength of bamboo scrimber with parallel grains. Sharma et al. [3] examined the influence of processing method on the mechanical performance of engineered bamboo for structural applications. Estévez-Cimadevila et al. [4] researched the performance of timber-concrete composite, and evaluated the effects of different tension systems on beam performance. Martins et al. [5] studied the bonding performance of Portuguese Maritime pine glulam. Nadir et al. [6] probed deep into the flexural stiffness and strength of the timber beams in the glulam made by horizontal stacking of two kinds of composite sheets: carbon fiber reinforced polymer (CFRP) and glass fiber reinforced polymer (GFRP).

As a major agricultural by-product, most crop stalks are treated as waste and burned directly. The burning of crop stalks emits lots of air pollutants, and causes a huge waste of resources. Therefore, it is of great importance to make comprehensive use of crop stalks. Despite being too variable to be prepared into high-quality building materials [7], natural cornstalks can be reconstituted and recombined into novel eco-friendly and cost-effective composites with great potential in the building industry. These novel composites have been utilized as decoration panels, thanks to their high density, high strength, and resistance to fire, corrosion, moisture, and insect. However, the application of these composites in building structures is not yet mature, calling for more research results on mechanics and materials science and basic theories on their application in structural design [8]. To promote the application, it is imperative to study the basic mechanical performance of glue-laminated cornstalk scrimber.

Taking cornstalks as the raw material, this paper processes cornstalks into a glulam scrimber by special techniques, without damaging the original fibers, followed by experimental analysis on the parallel-to-grain tensile performances of cornstalk scrimber and glue-laminated cornstalk scrimber. The research results lay a solid theoretical basis for the structural design and engineering application of novel cornstalk composites.

2. PERFORMANCE OF NOVEL CORNSTALK SCRIMBER UNDER AXIAL TENSION

2.1 Experimental Method

(1) Materials and instruments

The novel cornstalk scrimber was prepared through laying, stoving, sizing, drying, cold pressing, and curing of the stalk fibers obtained by removing the leaves and haulms of selected cornstalks.

The size of scrimber specimens was designed according to *Method of Testing in Tensile Strength Parallel to Grain of Wood* (GB/T 1938-2009) [9] and *Standard Test Methods for Small Clear Specimens of Timber* (ASTMD143-09) [10]. The total length of each specimen was 380mm, including a

700mm-long effective segment. Note that the length is measured parallel to grain. The transition is smooth between the effective segment and the clamping part at either end. The size and photo of the specimens are displayed in Figures 1 and 2, respectively. It was measured that the cornstalk scrimber has a density of 1.22g/cm^3 and a water content of 8.3%.

The instruments and accessories in our experiments include computerized electro-hydraulic servo universal testing machine WAW-600, static strain tester DH3818-2, extensometer, strain gauge, ohmmeter, etc.

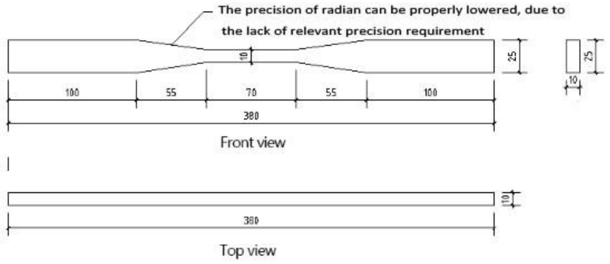

Figure 1. The size of each scrimber specimen (unit: mm)

Figure 2. The photo of scrimber specimens for axial tension experiments

(2) Experimental procedure

Each experiment consists of an elastic phase and a failure phase [11-14]. The Young's modulus of the specimen was measured in the elastic phase, and the tensile strength was captured in the failure phase [15, 16]. Specifically, each experiment was implemented in four steps:

Step 1. Preload each specimen to eliminate the effect of disturbances (e.g. the gap of the loading device) on the experiment [17].

Step 2. Apply tension to the specimen at a uniform rate. When the specimen deformed by 0.5mm, stop the loading and remove the extensometer [18].

Step 3. Continue with the loading process to damage the specimen in 1.5-2.0min, and measure the failure load to the accuracy of 100N [19, 20].

Step 4. If the damage was outside the effective segment, consider the results of the experiment as invalid and discard them [21].

2.2 Results Analysis

(1) Experimental phenomena and failure mechanism

Cornstalk fiber is a brittle material. During the experiments, with the increase of the load, the specimens gradually gave off a slight noise, indicating that the internal fibers were broken. No obvious sign of failure was observed on any specimen. Before the failure of any specimen, there was no apparent plastic deformation. Once the load reached to ultimate bearing capacity, the specimen would fracture all of a sudden. The fracture mainly occurred in the weak area in the middle, belonging to brittle failure. The test results are illustrated in Figures 3 and 4.

Figure 3. Flat damage;

Figure 4. Oblique damage

1) Flat damage

Most valid specimens suffered from flat damage, which mainly occurred in the effective segment. The main features of the damage include the simultaneous breaking of all fibers and a relative neat and flat cross-section of the facture.

The parallel-to-grain tensile performance of cornstalk scrimber mainly depends on the strength of longitudinal fibers. The higher the fiber content, the better the tensile strength of the specimen parallel to grain [12]. The mechanism of flat damage can be summarized as follows: If the cornstalk fibers are distributed evenly in the effective segment, the centroid of the specimen coincides with the axial point of the tensile force, such that the tensioned cross-section is under a uniform tension; therefore, the cornstalk fibers will break at almost the same time, when the specimen reaches its ultimate bearing capacity.

2) Oblique damage

A few valid specimens suffered from oblique damage, which also occurred in the effective segment. The oblique damage is characterized by a long facture not perpendicular to the direction of longitudinal fibers.

Table 1. The valid results of parallel-to-grain tensile experiments on cornstalk scrimber

Specimen number	Sectional area/mm^2	Ultimate load /N	Ultimate strength /MPa	Young's modulus /GPa
L1	110.25	3,300	29.9	15.76
L2	106.08	3,200	30.2	15.23
L3	112.32	3,600	32.1	17.59
L4	105.06	3,400	32.4	18.31
L6	97.92	2,300	23.5	16.04
L7	98.94	2,600	26.3	16.38

L8	111.28	3,800	34.1	17.92
L10	115.54	5,200	45	19.66
L12	100.98	2,400	23.8	15.65
L13	99.96	2,500	25	15.43

The mechanism of flat damage can be summarized as follows: Different parts of the specimen are tensioned in varied degrees, owing to the uneven distribution of fibers. The axial tensile force forms an additional bending moment at the centroid, resulting in different stresses on the two sides. Therefore, the fibers on the two sides will break at different moments, creating a crevasse with a certain angle.

(2) Data sorting and analysis

A total of 13 parallel-to-grain tensile experiments were conducted on cornstalk scrimber. Valid results were obtained from 10 experiments (Table 1).

(3) Parallel-to-grain strength

Statistical analysis on experimental data shows that, for the cornstalk scrimber specimens, the parallel-to-grain tensile strength averaged at 30.2MPa, with a variation coefficient of 20.2%, and the parallel-to-grain Young's modulus averaged at 16.8GPa, with a variation coefficient of 8.4%.

The variation coefficients of cornstalk scrimber specimens were within the acceptable range, indicating that the specimens have relatively stable tensile performance and the experimental data are highly credible. The variation coefficient of Young's modulus was smaller than that of the tensile strength. This means the Young's modulus of cornstalk scrimber specimens is more stable than tensile strength.

Comparing the data and damage states of different experiments, the flat damage specimens had far greater ultimate tensile strength than oblique damage specimens. This is because, compared with oblique damage specimens, the flat damage specimens face a uniform stress and have strong bearing capacity.

(4) Stress-strain relationship

The stress-strain model can describe the performance of materials under different load conditions. Figure 5 presents the stress-strain curves of valid specimens in the axial tension experiments.

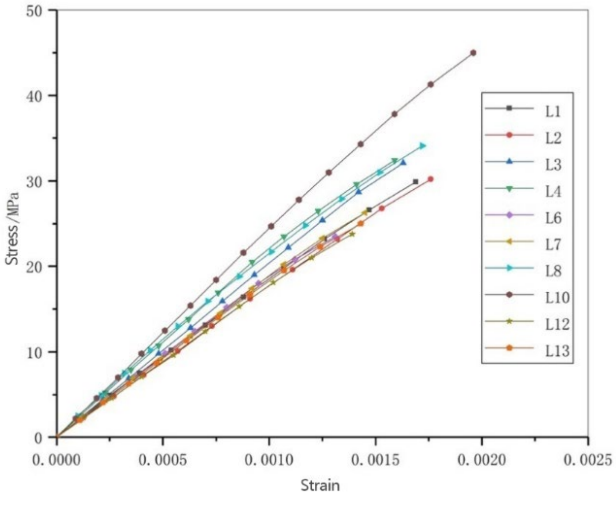

Figure 5. The parallel-to-grain stress-strain curves of valid specimens

As shown in Figure 5, the stress-strain curves of different specimens captured under the same load condition were slightly different in shape, but similar in overall trend. The slight difference is resulted from the discreteness of the material, and the numerous influencing factors in the experiments.

When the load increased continuously to a critical level, the specimens suddenly broke at their weak points. There was no obvious plastic phase, suggesting that the specimens suffered from brittle failure.

Before the load reached the critical level, the stress-strain relationship changed linearly. Therefore, the elastic performance and brittle failure features of cornstalk scrimber under parallel-to-grain axial tension can be illustrated with a single linear model.

3. PERFORMANCE OF NOVEL GLUE-LAMINATED CORNSTALK SCRIMBER UNDER AXIAL TENSION

3.1 Experimental methods

There are many ways to combine cornstalk scrimbers into glue-laminated cornstalk scrimber. Considering the decisive role of parallel-to-grain fiber strength on the tensile strength of axial tensile members, the glue-laminated cornstalk scrimber specimens for axial tension experiments were prepared by combining cornstalk scrimbers parallel to grain. The specimen preparation involves finger jointing, sanding, sizing, locking, butting, and polishing [13].

The size of each sample is shown in Figure 6. A total of 11 specimens were prepared. The sectional size was fixed at 16mm×54mm. The effective segments of the specimens were designed into three different lengths: 120mm, 180mm, and 240mm. The water content and density of the specimens were measured as 8.2% and 1.24 g/cm^3, respectively. The photo of these specimens is given in Figure 7.

The experimental procedure and instruments/accessories are the same as those in Subsection 2.1

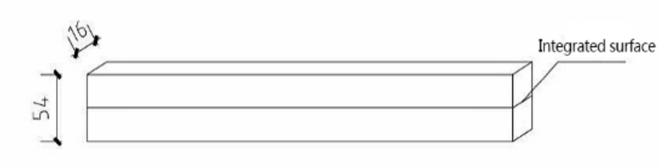

Figure 6. The size of each glue-laminated cornstalk scrimber specimen (unit: mm)

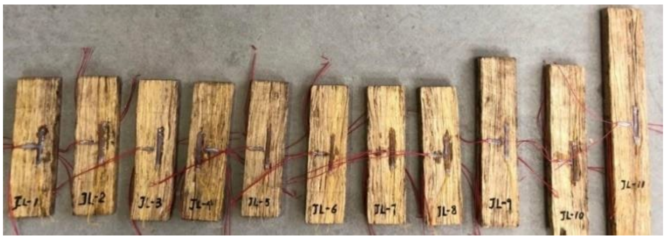

Figure 7. The photo of glue-laminated cornstalk scrimber specimens for axial tension experiments

3.2 Results analysis

(1) Experimental phenomena and failure mechanism

Glue-laminated cornstalk scrimber is a brittle material. During the experiments, the fibers broke under the growing load, giving off crisp sounds from the inside of the specimen. No plastic deformation or any obvious sign was observed before the specimen failed. The main failure modes observed in the 11 experiments were fracture damage and splitting damage (Figures 8 and 9).

1) Fracture damage

Under the fracture damage, the fibers in the specimen were torn apart, creating an irregular shaped crevasse. Some of the broken fibers were pulled out from the crevasse, causing the specimen to deform or fracture at the crevasse.

The main reason for fracture damage is as follows: the density is not evenly distributed in the cornstalk scrimber, due to disturbances in production and processing, resulting in a nonuniform stress distribution within the cornstalk scrimber; under axial tension, different parts of the glue-laminated cornstalk scrimber are under varied stresses; therefore, the specimen will be damaged at the weakest point, as the fibers are torn apart.

2) Splitting damage

Under the splitting damage, the fiber layers of the specimen cracked, while the longitudinal fibers were largely intact. The cracks were straight or oblique, and propagated parallel to grain. Eventually, the specimen was cracked along the crack or split into pieces.

The root cause of splitting damage is that the tensile strength of the glue-laminated cornstalk scrimber is weakened by the uneven sizing or insufficient cold pressing of cornstalk scrimber. The glue-laminated cornstalk scrimber is damaged before the longitudinal fibers fully exert its tensile performance.

In addition, the specimen with splitting damage is very likely to suffer from fracture damage in other parts. The stress uniformity of such a specimen is poorer than that of a specimen that only suffers from fracture failure. According to the tensile strength data measured in subsequent experiments, the specimen that only suffers from splitting failure had relatively weak ultimate tensile capacity. This is because the local fibers that actually bear the tensile force in the specimen have relatively weak strength.

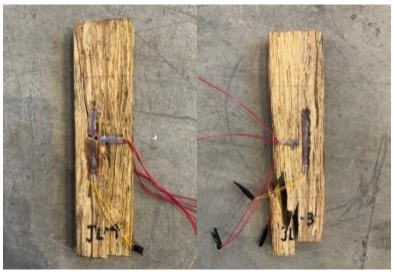

Figure 8. Fracture damage

Figure 9. Splitting damage

The damage of glue-laminated cornstalk scrimber did not occur on the bonding face, because the binder is much stronger than the fibers. The bonding face will not be damaged, as long as the binder is applied evenly between scrimbers. Therefore, the tensile strength of glue-laminated cornstalk scrimber is mainly affected by the strength of cornstalk scrimber and the material uniformity.

(2) Data sorting and analysis

Table 2 records the valid results of parallel-to-grain tensile experiments on glue-laminated cornstalk scrimber.

Table 2. The valid results of parallel-to-grain tensile experiments on glue-laminated cornstalk scrimber

Specimen number	Sectional area/mm^2	Ultimate load /N	Ultimate strength /MPa	Young's modulus /GPa
JL1	778.48	18,300	23.5	17.42
JL2	845.3	25,000	29.6	18.26
JL3	833.04	25,500	30.7	17.93
JL4	856.52	26,900	31.4	16.03
JL5	794.26	22,700	28.5	18.26
JL6	788.84	19,200	24.3	15.28
JL7	845.25	26,200	31	17.04
JL8	825.44	21,800	26.4	18.13
JL9	837.4	24,400	29.1	17.32
JL10	819.28	22,800	27.8	18.26
JL11	789.7	15,500	19.6	16.52

Since the cornstalk materials are from the same batch, five cornstalk scrimber specimens were also prepared for comparison. The shape and size of these specimens are the same as Figure 1. The average ultimate tensile strength of these specimens was measured as 27.1MPa.

By contrast, the tensile strength of glue-laminated cornstalk scrimber specimens averaged at 30.2MPa. Thus, glue-laminated cornstalk scrimber is slightly stronger than or as strong as its basic component (cornstalk scrimber). The combination of cornstalk scrimbers does not bring great changes to the tensile strength of the material.

Under the same experimental conditions, the parallel-to-grain tensile strengths of cornstalk scrimber specimens averaged at 30.2MPa. This means cornstalk materials in different batches only differ slightly in mechanical performance.

(3) Parallel-to-grain strength

As measured in the experiments, the parallel-to-grain tensile strength of glue-laminated cornstalk scrimber specimens averaged at 27.3MPa, with a variation coefficient of 13.2%, and the parallel-to-grain Young's modulus averaged at 17.22GPa, with a variation coefficient of 5.6%.

The variation coefficients indicate that the specimens have relatively stable tensile performance and the experimental data are highly credible. The variation coefficient of Young's modulus was obviously smaller than that of the tensile strength, revealing that the parallel-to-grain Young's modulus is more stable than tensile strength.

Comparing the two damage states, the splitting damage specimens had far smaller tensile strength than fracture damage specimens. A possible reason is that fewer fibers in the splitting damage specimens bear the tensile force than those in the fracture damage specimens. The fracture damage specimens are stronger under tensile load, because virtually no bonding between cornstalk scrimbers becomes ineffective, causing the strength to decline. Besides, the experimental data show that, the longer the specimen, the weaker the tensile strength.

(4) Load-strain relationship

Considering their large size, the macro changes of glue-laminated cornstalk scrimber specimens were observed by plotting the load-strain curves (Figure 10).

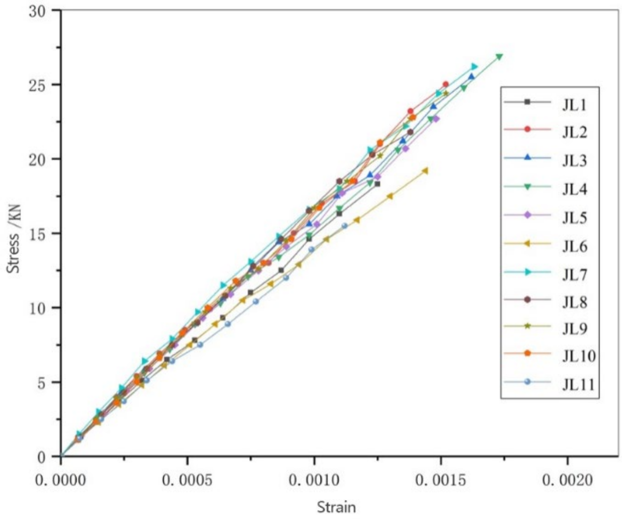

Figure 10. The load-strain curves of glue-laminated cornstalk scrimber specimens

As shown in Figure 10, the load-strain curves of different specimens captured under the same load condition were slightly different in shape, but similar in overall trend. The slight difference stems from the internal material variation of each specimen, and other influencing factors in the experiments.

No obvious plastic phase was observed from the start of loading to the sudden brittle failure of the specimens. Overall, the load-strain curves changed linearly, despite fluctuations in the middle and later stages of the experiments. The reason is that, with the growth of tensile load, the internal fibers of each specimen are broken or partially damaged, causing a slight drop in internal force. However, the overall specimen has not reached the ultimate bearing state. Then, the internal stress in the specimen will redistribute, and start to increase again.

4. CONCLUSIONS

This paper carries out experimental analysis on the tensile performance of glue-laminated cornstalk scrimber. The main conclusions are as follows:

(1) For both cornstalk scrimber and glue-laminated cornstalk scrimber, the parallel-to-grain Young's modulus is more stable than tensile strength. If the cornstalks are of the same batch, glue-laminated cornstalk scrimber is slightly stronger than or as strong as cornstalk scrimber.

(2) Both cornstalk scrimber and glue-laminated cornstalk scrimber suffered from brittle failure without any obvious signs. Many more cornstalk scrimber specimens suffered from flat damage than oblique damage. The flat damage specimens have much greater ultimate bearing capacity than oblique damage specimens. The main failure modes observed from glue-laminated cornstalk scrimber specimens were fracture damage and splitting damage. The tensile strength of glue-laminated cornstalk scrimber is negatively correlated with the degree of splitting damage.

(3) Under parallel-to-grain tensile force, the stress-strain relationship of cornstalk scrimber changes linearly. The tensile performance of the material under different load levels can be described with a single linear stress-strain model. For glue-laminated cornstalk scrimber, the load-strain curve basically changes linearly.

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