Breaking Behaviour of Wheat Stem Undergoing Multiple Forces Combination Sequence during Threshing Process

B. Zhang[1], Z. Tang[1*], M. Wang[1], and Y. Li[1]

ABSTRACT

During threshing process, wheat stems are easily broken when subjected to the combined forces of continuous tension, bending and compression of threshing bars. To reveal the causes of breakage, it is very significant to study the broken morphology and minimum breaking force of wheat stems undergoing multiple forces combination sequence. In this study, the mechanical characteristics of wheat stems undergoing single and combined forces were tested and analyzed. The results showed that when wheat stems are subjected to single load, the internodes are easiest to be broken under tensile force. When mixed-mode conditions of various forces are applied, the internodes are most easily broken under the combination of cantilever beam bending and three-point tension and the nodes of wheat are most prone to breakage when subjected to three-point compression. Under all loading states, the nodes of wheat are most prone to breakage when subjected to three-point compression. The damaged areas of internodes tend to be broken more easily. Consequently, the research of minimum breaking force of wheat stems undergoing multiple forces combination sequence reveals the substance of the breakage of wheat stems during threshing process.

Keywords: Breaking force, Broken morphology, Combination way, Minimum force spectrum.

INTRODUCTON

Wheat is one of the major grain crops widely cultivated around the world. Wheat is also the food crop with the highest yield and ranks first among cereals (Gobbett *et al*., 2017; Markowski *et al*., 2013). In 2019, global wheat production was about 765 million tons. Moreover, world demand for wheat is growing at approximately 2% per year (Gummadov *et al*., 2015). Mechanized harvesting of wheat not only improves harvesting efficiency, but also effectively reduces wheat planting costs. Wheat combine harvester integrates cutting, threshing, cleaning and separation, which greatly reduces the burden for farmers. However, the broken stems produced by threshing cylinder can be mixed with the grain, which seriously affects the subsequent grain cleaning. Therefore, it is very important to reveal the essence of the breakage of wheat stems during threshing process.

Mechanical properties of wheat stems are important factors in resisting breakage during threshing. Studying the structure and mechanical properties of wheat stem can provide a basis for revealing the reason of breakage and fracture of wheat stems. Wheat stem vascular bundles have special material with mechanical characteristics. Duan *et al*. (2003) indicated that there were some effects of wheat stem vascular bundles on the flexural rigidity. It was characterized by multiphase, non-uniformity and anisotropy. Stress of wheat stems was not only related to strain but also to flow factors. To study the

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[1] Key Laboratory of Modern Agricultural Equipment and Technology of Ministry of Education, Jiangsu University, 212013, Jiangsu, People Republic of China.
* Corresponding author; e-mail: tangzhong2012@126.com

mechanical properties of wheat stems, many researchers have studied the mechanical tests of wheat stems, such as tension, compression, bending and torsion (Chandio *et al*., 2013; Neenan *et al*., 1975; Huang *et al*., 2018a). The mechanical properties such as the strength limit and flexural modulus of wheat stems and wheat roots were determined by tension and bending tests on a universal testing machine. Notably, the mechanical tests of wheat stems are directly related to the stem nodes and vascular bundles.

Cross sectional diameter and wall thickness of wheat stems decrease gradually from bottom to top. Therefore, the tensile and bending characteristics of wheat stem also change significantly. However, the combined characteristics of wheat stem inner core and outer sheath on the breaking resistance of stems are still unclear. The stalk of wheat is composed of knots, inner core and outer sheath. Moreover, during the maturity period, the epidermal cells of the internodal epidermis and vascular bundles of wheat stalks undergo silicification and lignification to varying degrees. These all have a greater impact on the mechanical strength of wheat stalks (Hu *et al*., 2007). By studying the mechanical properties of roots and stems of wheat during maturity, Guo *et al*. (2019) not only achieved the stress-strains curve of wheat roots, stems and leaves under the four basic deformation conditions of tension, bending, compression and shear, but also obtained the main evaluation indicators that characterize the strength, stiffness and stability of roots, stems and leaves. In addition, by analyzing the deformation and failure laws of roots, stems and leaves under external forces, they learned that wheat roots, stems and leaves have different strengths and stiffness. Huang *et al*. (2018b) indicated that there are large differences in the elastic modulus of different wheat stems by carrying out tensile tests on stems of wheat with a universal tensile tester. The above results all reveal the influence of wheat stems structure on the load-bearing capacity of stems during tension, compression and bending.

The influence of different loads on the deformation of the leaf spring was analyzed by Wang *et al*. (2009). They obtained the relationship between the spring load and the bending deformation. These results provide a theoretical basis for the strength check and design calculation of the combined force. The important characteristic parameters such as torque curve, bending moment-span deflection curve and section strain distribution of wheat stem determines the breaking characteristics. The breaking behavior, ultimate bearing capacity, strain distribution of the composite box girder under the combined bending and torsion behavior and the relative slip law between the steel beam and the concrete slab joint surface were also obtained (Hang *et al*., 2012). These show that the stress of wheat stems during the threshing process is complex, not simply the tension, compression, bending and other single kind of forces, but a combination of multiple forces mode. However, researchers are still unclear about the morphological and intrinsic changes of wheat stems under combined forces. This is also an important reason why it is difficult to reduce the breakage of wheat after threshing.

In this research, we aimed to reveal the reason of breakage of wheat stems and the easiest way to break the wheat stems during threshing, and to analyze the damage characteristics of wheat stems under different force combination ways. The easiest broken route for wheat stem undergoing multiple force combination sequence was obtained by analyzing the combination of tension, compression and bending of wheat stems. Then the minimum breaking force of wheat stem undergoing multiple force combination sequence was determined to reveal the essence of the breakage of wheat stem during threshing. The stem breaking morphological features of wheat was verified by threshing test in field.

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MATERIALS AND METHODS

Wheat Stems Structure Characteristics

Wheat stem is composed of internode vascular bundles, which has the function of support, transport, photosynthesis and storage. The lower layer of wheat stem constitutes the support layer of the population. The upper layer and the leaves together constitute the photosynthetic layer of the population (Abbas *et al.*, 2019; Guo *et al.*, 2009). Wheat stem can be divided into two parts, one part above the ground and the other one below the ground. The underground joints do not elongate to form a branching section (Oscar *et al.*, 2017). Wheat stem is composed of nodes and elongated internodes. The number of wheat stem nodes is generally 4 to 6. The appearance and structural characteristics of wheat stem are shown in Figure 1.

As shown in Figure 1, the first internode of the wheat is the shortest one, increasing upwards. The internode under the panicle is the longest, accounting for almost half of the total length of all internodes, nearly around 40-50%. The difference in plant height mainly depends on the length of the internodes rather than the number of internodes. The diameter of wheat stems is usually thinner and the first section was thickest. Then, thickness of the stem wall is gradually thinner from the bottom to the top.

Sample Preparation

The object of this paper is the representative wheat variety *Zhenmai 168* in Danyang City (latitude 31° 99´ N and longitude 119° 57´ E), Jiangsu Province, China. The cropping system is mainly winter wheat (always from September to the next May). The soil texture is loam, which is convenient for drainage and irrigation. The average rainfall during wheat growth is about 455 mm. The natural height of wheat plant is 900 to 950 mm. Length of panicle is 64 to 68 mm. Ratio of grain quality to whole plant stem mass is 1.4 to 1.6. Grain weight is 36 to 40 g, and the wheat yield is 5,250 to 6000 kg hm^{-1}. At the time of harvest, the grain moisture content and stem water content are 13.5-15.5 and 40.4 - 45.8%, respectively.

The wheat samples used in the experiment were harvested from the field when the wheat matured in May. During the experiment, protection work was carried out on the wheat to ensure that the moisture content of the wheat stalk remained unchanged. Before the experiment, the internodes and nodes of the wheat stalk were cut, with a length of 80±2 mm. Since each group of the experiments were repeated 6 times, 10 samples were prepared for each group of experiments (4 of them as spare), as shown in Figure 2.

The damage modes of the wheat stem depend on their mechanical properties. We characterized their properties by applying different loading modes using an Edberg 0824 push-pull testing device (Figure 2), from Shenzhen Xindeya Precision Instrument Co., Ltd., China. The embedded software displays and records the force and displacement data in real time. Table 1 shows the technical parameters of the device.

Mechanical Testing

The damage degree after de-granulation of wheat stems depends on the ability of stems to withstand threshing power. The mechanical properties of wheat stems are important indicators reflecting the causes of stem damage after threshing (Naik *et al.*, 2018). To analyze the characteristics of wheat stems under different loading modes, the tests of internodes (mainly internodes with leaf sheath) and nodes subjected to tension, bending and compression force were carried out (Luo *et al.*, 2019; Zhou *et al.*, 2019).

As shown in Figure 3, in mode (a), vertical tension is applied on both ends of the stems

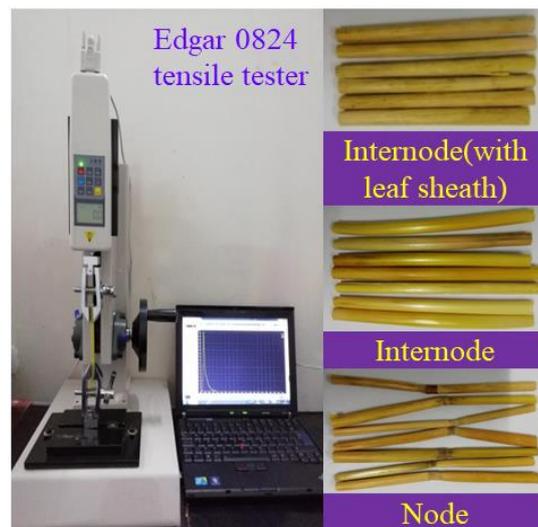**Figure 1.** Morphology of wheat stem.   **Figure 2.** Equipment and samples.

Table 1. Technical parameters of the Edberg 0824 push-pull testing machine.

Parameter	Value/Unit
Model	HP-200
Test distance accuracy	0.1 mm
Test force accuracy	0.5%
sensors	Built-in pressure sensor
Test distance range	0.1~180 mm
Power range	+/-20 kg
PC interface	RS232C standard port or USB port
Operating temperature	-20 ~70°C

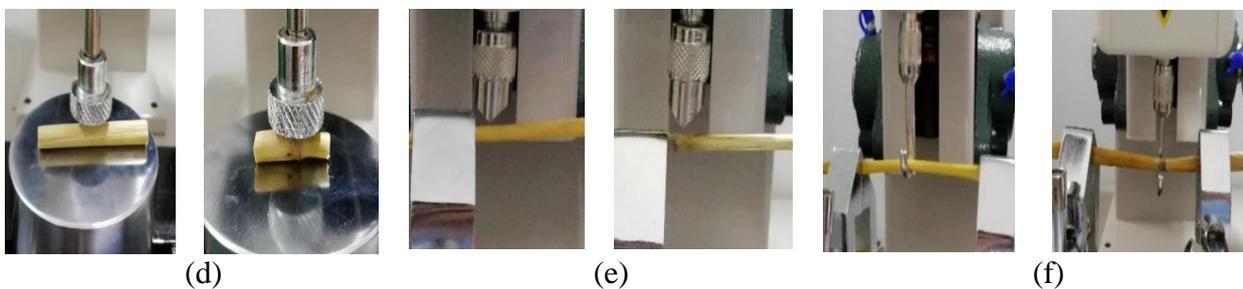(d)   (e)   (f)

Figure 3. The method of pulling, pressing and bending of wheat stems.

and bending stiffness is characterized under three-point bending as in mode (b). Mode (c) is axial compression; mode (d) tests the radial compression; mode (e) is cantilever beam bending; and mode (f) reveals the three-point tensile performance (different from mode (b) in that the stem is fixed at the ends). Similar test methods above have also been reported by some researchers (Bochkarev *et al*., 2019; Aaron *et al*., 2018; Shah *et al*., 2017). All samples were tested under a loading rate of 1 mm s^{-1}.

The main steps of the axial tension test are as follows: Firstly, the upper and lower ends of the wheat stem are clamped by a clamp. Then, the Edberg 0824 push-pull test machine is calibrated and zeroed. Finally, the samples are subjected to tensile force and the data is tested (Tang *et al*., 2019). Other types of test operations are similar. Each kind of test was repeated six times. The combined loading test means that the wheat stems that were not broken after being subjected to a single loading force were

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| (a) Combine harvester | (b) Threshing structure | (c) Wheat threshing |
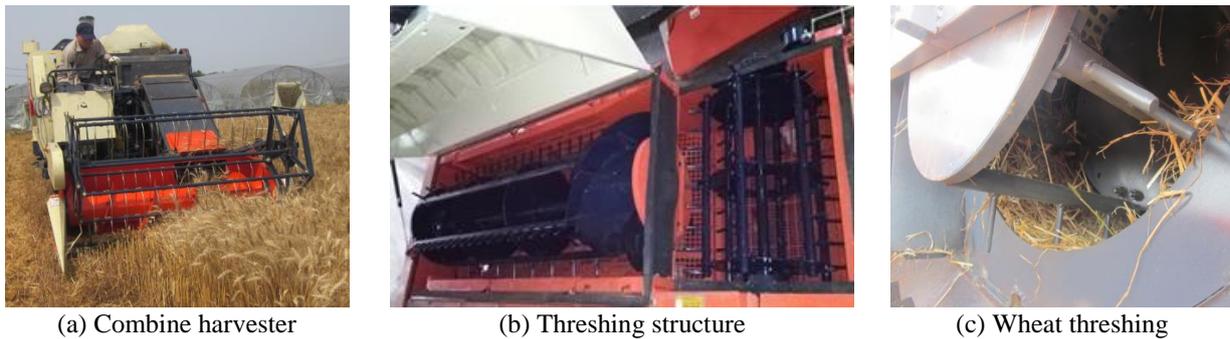
Figure 4. Scene of combine harvester harvesting wheat in a field and threshing structure.

further tested with other different loading forces until the stalks completely broke.

In-Field Threshing Test

To verify the breaking characteristics of wheat stems after being threshed by combine harvester, broken wheat stems were collected and analyzed after de-granulation and separation of combine harvester. The structure of combine harvester and the threshing separation device is shown in Figure 4.

The combine harvester owes its name to the integration of the whole chain of grain harvesting steps in one machine. The threshing and separating device of wheat combine harvester consisted of a tangential axial threshing cylinder and a longitudinal axial threshing cylinder (Fu *et al*., 2018). When wheat is threshed, it is fed into the tangential axial threshing cylinder through the mixing and conveying trough for initial separation, and then enters the longitudinal axial threshing cylinder for re-separation and, finally, wheat stems are removed from the grass drain.

Statistical Analysis

The complete parameter estimation procedure and the results of all tests were repeated six times to reduce the impact of random influence on choice of validation set. Means±Standard Errors (SE) were calculated using the same variables (n= 6). The mean data were analyzed statistically using one-way Analysis Of Variance (ANOVA), with a general linear model, in SPSS software (v. 25.0, SPSS Inc., CA, USA), then, mean results were compared by the Least Significant Difference (LSD) post-hoc test at the 5% significance level (P< 0.05).

RESULTS AND DISCUSSION

Mechanical Characteristics of Wheat Stem Undergoing Single Force

To facilitate the analysis of the mechanical characteristics of wheat stems, the peak range of tensile, compressive, and bending bearing capacity of the wheat stem was tested. The results are shown in Table 2.

As shown in Table 2, when subjected to different loading modes, the internodes were broken only under axial tension and three-point tension. The internodes only buckle under the other four loading modes and the bearing capacity of the internodes subjected to vertical compression is greater. The maximum force of internodes bending buckling is 54.3±6.3 N and the minimum force required for the internodes to break is 64.2±2.0 N. If the minimum breaking force of the wheat stem can be found, this will effectively reduce the energy consumption during the harvesting process (Busato and Berruto, 2016). A straw-sweep-soil model was developed using the DEM (Zeng *et al*.,

Table 2. Summary of mechanical performance of the internodes under different loading modes.

Internode	Test type	Fracture or not	Peak load/N	Mean/ N	SE[a]
1	Axial tension	Yes	130~170	148.0	15.3
2	Three-point tension	Yes	60~70	64.2	2.0
3	Axial compression	No	45~65	54.3	6.3
4	Radial compression	No	15~20	18.9	1.3
5	Cantilever beam bending	No	2.5~3.0	2.9	0.05
6	Three-point bending	No	2.0~5.5	3.6	1.3

[a] SE is the "Standard Error".

2019). The model was able to simulate dynamic attributes of bulk materials and individual particles. In this paper, the wheat stem critical breaking forces were tested. These results can be used to determine the modelling parameters of wheat stem.

The nodes were tested under different loading modes and results were summarized in Table 3.

As shown in Table 3, when subjected to different loading modes, the nodes were easily broken, except for the radial compression. The compression strength of node was significantly greater (P< 0.05) than tensile and bending strength. The nodes were easily broken under bending condition, indicating the brittleness of wheat node. Thus, the nodes are vulnerable to axial force.

Mechanical Characteristics of Wheat Stem under Combined Forces

Internodes are difficult to break under the compression or bending force alone and the nodes only buckle under single radial compression, which indicates the fracture of

wheat stems may contributed to the combined forces. Combined loading modes were applied to wheat internode and node. The buckling samples were further applied with tensile force. Figure 5 shows the mechanical performance of wheat stems under combined loading conditions.

As shown in Figure 5, there were many fractures on the surface of the internodes that were subjected to combination of compression and tension. The shape of the rupture is the breaking along the indentation. The bearing capacity curve of internodes appears as a slow upward trend in the early stage and has ups and downs, then, the curve increased until it finally returned to zero in the later period. The peak capacity of stem rupture ranged from 30 to 35 N with an average of 32.4±0.9 N.

The bearing capacity of internodes subjected to combined loading modes and single tension force were compared, as shown in Table 4.

As shown in Table 4, when internodes were subjected to combination of compression and axial tension, the average value of breakage was 78.0±15.9 N, which

Table 3. Summary of mechanical performance of the nodes under different loading modes.

Node	Test type	Fracture or not	Peak load/N	Mean/ N	SE[a]
1	Axial tension	Yes	55~90	70.9	12.2
2	Three-point tension	Yes	25~30	28.4	1.10
3	Axial compression	Yes	90~120	102.5	10.5
4	Radial compression	No	10~25	18.6	4.70
5	Cantilever beam bending	Yes	15~30	22.5	2.90
6	Three-point bending	Yes	10~15	11.4	0.70

[a] SE is the "Standard Error".

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(a) Broken morphology
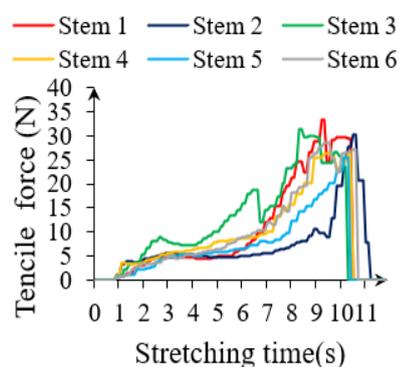
(b) Bearing capacity curve of internode

Figure 5. Mechanical characteristics of internodes under combined loading modes.

Table 4. Comparison of bearing capacity of internodes under different loadings.

Internode	Test type	Fracture or not	Peak load/N	Mean/N	SE[a]	Broken shape
1	Axial tension	Yes	130-170	148.0	15.3	Jagged fluctuation
2	Compression and axial tension	Yes	60-105	78.0	15.9	Misaligned fracture
3	Bending and axial tension	Yes	115-145	129.5	8.9	Break along the bend
4	Three-point tension	Yes	60-70	64.2	2.0	Multi-segment fluctuation
5	Compression and three-point tension	Yes	30-35	32.4	0.9	Breaking along the indentation
6	Bending and three-point tension	Yes	8-12	9.2	1.0	Misaligned fracture

[a] SE is the "Standard Error".

Table 5. Comparison of bearing capacity of nodes under different loadings.

Node	Test type	Fracture or not	Peak load /N	Mean/N	SE[a]	Broken shape
1	Axial tension	Yes	55-90	70.9	12.20	Breaking at the node
2	Three-point tension	Yes	25-30	28.4	1.10	Breaking at the node
3	Bending and axial tension	Yes	60-80	70.8	4.80	Breaking at the node
4	Bending and three-point tension	Yes	10-20	15.4	2.00	Breaking at the node

[a] SE is the "Standard Error".

was significantly smaller (P< 0.05) than single axial tension. Comparing the internodes under combination of bending and three-point tension and that under single axial tension, the critical fracture force of the former is significantly smaller (P< 0.05) than the latter. The internodes with bending and compressing damage can be easily

broken under tension. Besides, the damaged areas of wheat stalks tend to be broken more easily.

The bearing capacity of nodes subjected to combined loading modes and single tension force were compared. As shown in Table 5, the critical force of the node subjected to combined loading modes is similar to that of single force. Therefore, the bending and compressing damage has little effect on the tensile breaking of the node.

DISCUSSION

Comparison of Internodes and Nodes under Single Force

Comparing the mechanical test of the internodes and nodes, as shown in Figure 6, the nodes are more susceptible to rupture than internodes. This is mainly because the nodes are brittle and the internodes are composed of vascular bundles and lignin, which have stronger bearing capacity (Okuno *et al.*, 2014).

Minimum Force Spectrum for Wheat Stem to Break under Combined Forces

To determine the minimum force spectrum for wheat stems to break under combined forces, the loading path of the internodes
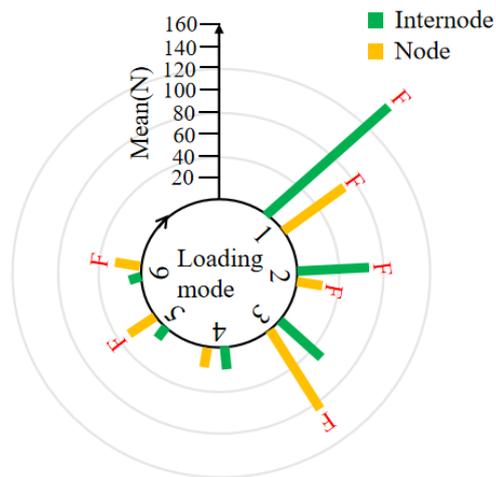
1 Axial tesion   2 Three-point tension
3 Axial compression   4 Radial compression
5 Cantilever beam bending   6 Three-point bending

Figure 6. Comparison between internode and node. "F" means Fracture.

subjected to different forces is summarized and shown in Figure 7.

It can be seen from Figure 7 that the internodes broke under all the mixture of six different stresses. The internodes can be broken after being subjected to radial compression (15 to 20 N) and three-point tension (30 to 35 N). Besides, the internodes also can easily break under cantilevered bending (2.5 to 3 N) and three-point tension (8 to 12 N). Comparing all routes to break internodes, the most vulnerable path to break internodes is through cantilevered bending
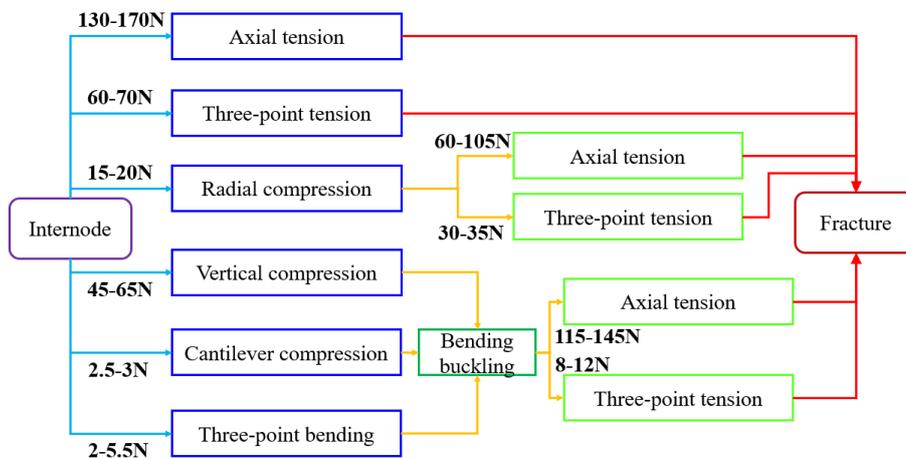

Figure 7. Minimum force spectrum for internodes to break under combined forces.
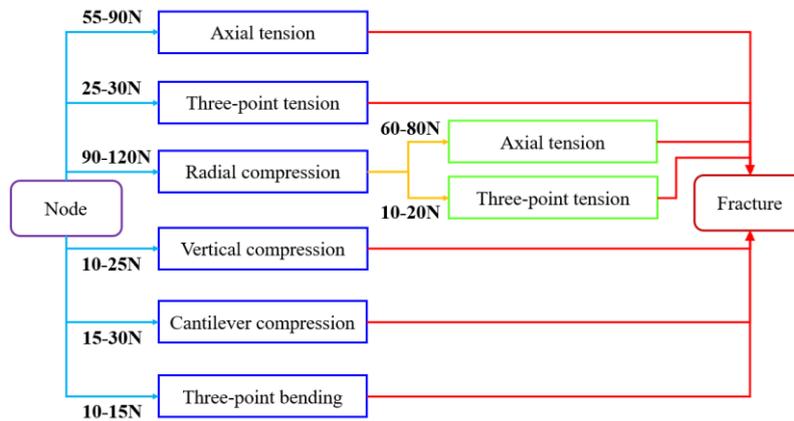
Figure 8. Minimum force spectrum required for nodes to break under combined forces.

and then three-point bending.

As shown in Figure 8, the minimum force required for nodes to break is 10 to 15 N, when subjected to three-point compression. Comparing the force spectrum of internodes and nodes under different loading conditions, internodes can easily break under combined force, while fracture of nodes only needs three-point compressing force. Under this condition, the position of rupture of internodes is at the indentation and that of nodes is at the node. The nodes are more likely to break than the internodes.

Difference in Mechanical Properties of the Whole Wheat Stem

According to the size of the stem section, the stem of a wheat plant can be divided into three parts: upper part, middle part and lower part. The cross-sectional area of wheat stem decreases from bottom to top. The mechanical properties of the upper, middle and lower parts of the wheat stem were tested separately by the determined minimum force spectrum. The breaking force curve of the internodes subjected to combination of cantilevered compression and three-point tension is shown in Figure 9.

Integrating Figures 6 and 9, the minimum forces required for the breaking of the top, middle, and root of the internodes when subjected to combined forces are 7-9, 25-28, and 30-35 N, respectively. Under the same combined force, the top part of wheat stem is significantly easier (P< 0.05) to break than the middle part and the lower part.

Leblicq *et al*. (2016) developed the crop stems model with data based on contact models. Individual stem and bulk compression capacity were analyzed by
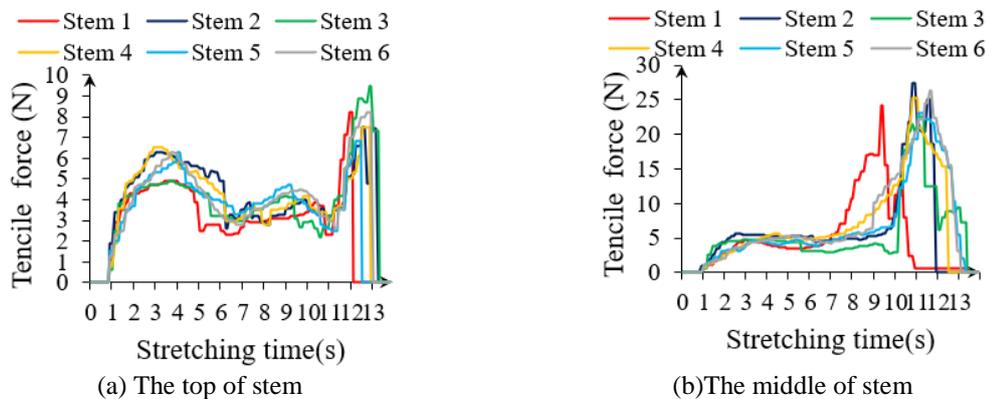

(a) The top of stem   (b)The middle of stem

Figure 9. Breaking force curve of internodes under combined loading modes.

comparison of simulations and measurements. The elastic modulus of the samples was measured and it was from 2.11 to 2.87 GPa. Hirai *et al*. (2003) analyzed the reaction force of a rice stem undergoing forced displacement based on a mechanical model of a crop stem and derived an equation of curvature describing rice stem bending by considering the curvature due to intrinsic shape. Combined with previous scholars'researches on the structural properties of crop stalks (Leblicq *et al.*, 2016; Hirai *et al.*, 2003), the properties of wheat stalks need further research.

Combine Harvester Field Wheat Harvest

To analyze the breaking characteristics of wheat stem undergoing different forces in the combine harvester threshing separation device, the wheat stem subjected to threshing were sampled. The results are shown in Figure 10.

As shown in Figure 10, the wheat stems breakage characteristics after threshing by the combine harvester were mostly radial compression indentations and there were fractures at the indentation. Although it is easy to buckle wheat stems by applying compression and bending force, wheat stems cannot be broken easily in this way, indicating the inevitable existence of combined forces. In addition, the nodes are more likely to be broke than the internodes. The order of most easily broken position of wheat stem is the top, middle, and root.

It can be seen that the rupture of wheat stem after threshing in the field by combine harvester is consistent with the results of the analysis and the conclusions obtained. Many researchers have studied the granule rupture form, stems deformation model and grain characteristics in the threshing process; and relatively good threshing models have been established Lenaerts *et al*.,2014; Leblicq *et al*., 2015). The aforementioned results of the study on stem rupture can be used to analyze the causes of stem breakage during
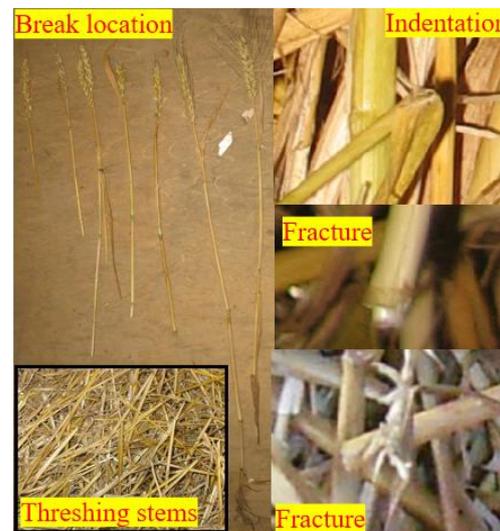
Figure 10. Breaking characteristics of wheat stem after threshing by combine harvester.

threshing. By analyzing the breaking characteristics of wheat stem and establishing stem modelling, the optimal wheat harvest time can be selected (He *et al*., 2018). By controlling the stem breakage during wheat threshing, the power used for threshing can be greatly reduced, which will also bring great benefits to subsequent grain cleaning. If there were few broken stems after threshing, the cleaning device of the combine can be greatly simplified.

CONCLUSIONS

The following conclusions were drawn from this experiment: When wheat stems were subjected to single load, the internodes were the easiest to break under tensile force. Although the internodes can be easily buckled by applying compression and bending force, they cannot be broken under such condition. Differently, the nodes buckled only under radical compression and could easily break under other single forces. The nodes were vulnerable to axial force. The node was more susceptible to rupture than the internode. When subjected to the combined forces, the internodes were most likely to be broken under the combination of

cantilever beam bending and three-point tension. Under all loading states, the nodes of wheat were most prone to breakage when subjected to three-point compression. The damaged areas of internodes tended to break more easily. Under the same combined force, the top part of wheat stem was more susceptible to fracture than the middle and the lower part.

ACKNOWLEDGEMENTS

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چگونگی شکسته شدن ساقه گندم تحت توالی ترکیب نیروهای چندگانه در طی فرایند خرمنکوبی

ب. ژانگ، ز. تنگ، ، م. وانگ، و ی. لی

چکیده

در طی فرایند خرمنکوبی، ساقه های گندم که تحت نیروهای ترکیبی کشش مداوم، خمش، و فشرده سازی میله های خرمنکوبی قرار می گیرند به آسانی شکسته و خورد می شود. به منظور مشخص کردن عوامل این شکستن، بسیارمهم است که مورفولوژی قطعات شکسته و حداقل نیروی شکست ساقه های گندم تحت توالی ترکیب نیروهای چندگانه بررسی شود. در این پژوهش، ویژگی های مکانیکی ساقه گندم تحت اثر یک نیروترکیب چند نیرو مورد بررسی و تحلیل قرار گرفت. نتایج نشان داد که هنگامی که ساقه گندم تحت اثر یک نیرو قرار می گیرد، قسمت میانگره‌ها در اثر نیروی کششی آسان‌تر از دیگر قسمت‌ها شکسته می شود. هنگامیکه ترکیبی از نیروهای مختلف اعمال می شود، میانگره‌ها به راحتی تحت ترکیب خمش تیر کنسول و کشش سه نقطه شکسته می شوند و گره‌های گندم زمانی که تحت فشار سه نقطه ای قرار می گیرند بیشتر در معرض شکستگی هستند. در تمام حالت های بارگذاری، گره‌های گندم زمانی که تحت فشار سه نقطه ای قرار می گیرند بیشتر مستعد شکستگی هستند. همچنین، قسمتهای صدمه دیده میانگره‌ها راحت تر شکسته می شود. در نتیجه، بررسی حداقل نیروی شکستن ساقه گندم تحت توالی ترکیب نیروهای چندگانه، چگونگی شکستن ساقه گندم را در طی فرآیند خرمنکوبی نشان می دهد.