EXAMINATION OF CALCULATION METHOD FOR THE FLEXURAL RIGIDITY OF CROP STALKS

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ABSTRACT

Calculation of the flexural rigidity value (EI) is indispensable for prescription of deflection characteristics of crop stalks in harvesting. Conventionally, EI has been determined by either average EI of the whole stalk or average EI of each stems divided into node through the calculation method of cantilever with homogeneous section. However, deflection characteristics of crop stalks caused by mechanical operation such as combine harvester were not exactly presumed by these conventional EI through the experiment by authors. Further, actual EI of a stalk changes in company with a change of moisture contents as time passes during the experiment. Finally, efficient calculation method for determining EI is needed in order to improve these problems.

In this study, mechanical model based on actual structure of the crop stalk with variety sectional area was proposed. This mechanical model is calculated by the theory of cantilever with continuous stages. Therefore, improvement of both calculating accuracy on EI and efficiency of measuring system was tried. At first, this calculation method was applied to piano wire of which EI was recognized in advance. As a result, EI calculated from this new method coincided approximately with piano wire's EI. Next, applying to crop stalks as same as piano wire, relationship between loads acting on crop stalks and deflection values calculated by EI using this new calculation method was exactly presumed in comparison with conventional method. Further, measuring time of deflection test was greatly reduced.

Finally, new calculation method of EI will be available for estimating mechanical characteristics of so many kinds of crop stalks in harvesting operation. Further, in this study, new deflection test using image-processing apparatus by computer will be introduced.

Key Word : Flexural rigidity, Deflection characteristics, Combine reel, Variety sectional area, Mechanical model of crop stalks

INTRODUCTION

Measurement of mechanical properties of crops is indispensable in order to make clear interaction between machine and crops in harvesting and further establish optimum machine harvesting fitted to crop condition. Concerning conventional studies on physical property of crops, compression characteristic and modulus of longitudinal elasticity in various rice stalks were measured by Esaki (1958), mechanical strength in rice and wheat stalks for inspecting lodging characteristics of crops caused by wind of cultivated land was measured by Inoue (1963), mechanical characteristic of stems of lodged paddy was examined by Morita and Tatani (1957), the flexural rigidity of wheat stalks was calculated by Mueller (1988). However, on above mentioned studies, basic physical properties were only measured. That means, mechanical properties, which are needed to make clear mechanical interaction between machine and crop stalks in harvesting, haven't been measured yet.

On the other hand, in recent years, deflection characteristics of rice stalks caused by a combine reel operation in harvesting were presumed by the large deflection equation of elastic beam and as a result, availability of this equation was examined by authors (1998). And also the equation for identification of EI at an arbitrary point of rice stalks where combine reel operates, was proposed. Furthermore, in this study, mechanical model based on actual structure of the crop stalk with variety sectional area was proposed. New calculation method of this mechanical model by the theory of cantilever with continuous stages was shown. Therefore, efficiency of this new calculation method was examined through deflection test. Further, deflection test improved by introducing the new calculation method was examined.

THE DEFLECTION EQUATION

The large deflection equation of elastic beam with homogeneous section

In recent years, the equation describing large deflection of crop stalk by reel operation was proposed by authors. Further, availability of this equation was examined by comparison with conventional small deflection equation of elastic beam. This equation is as follows;

$$\frac{d\omega}{dx} = \frac{lx - \frac{x^2}{2}}{\sqrt{\left(\frac{EI}{P}\right)^2 - \left(lx - \frac{x^2}{2}\right)^2}} \tag{1}$$

EI : the flexural rigidity [N·mm^2]
P : load acting on the cantilever [N]
l : the height from the fixed end of cantilever to the point of load acting on the cantilever [mm]
ω : deflection [mm]
x : the height from the fixed end of cantilever to an arbitrary point [mm]

Now, this large deflection equation was derived from cantilever with homogeneous section, then in this equation, EI of crop stalk is constant for all sections.

The large deflection equation of elastic beam with variety sectional area

EI value of crop stalks with variety sectional area changes in company with a change of their section. Therefore, we cannot accurately presume deflection characteristics of crop stalks by Eq.(1). Then, mechanical model based on actual structure of the crop stalk with variety sectional area, which changes EI value in each stems divided into node, was proposed as shown in Fig.1. And the large deflection equation of elastic beam with variety sectional area as shown bellow was derived from this mechanical model by the theory of cantilever with continuous stages.

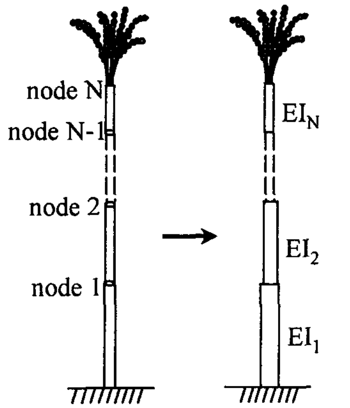

Fig.1. Model of the crop stalk with continuous stages

i) $n=1\ (0 \le x \le x_1)$

$$\frac{d\omega}{dx}=\frac{lx-\frac{x^2}{2}}{\sqrt{\left(\frac{EI_n}{P}\right)^2-\left(lx-\frac{x^2}{2}\right)^2}}$$

ii) $n \ge 2\ (x_{n-1} \le x \le x_n)$

$$\frac{d\omega}{dx}=\frac{lx-\frac{x^2}{2}}{\sqrt{\left(\frac{EI_n}{P}\right)^2-\left(lx-\frac{x^2}{2}\right)^2}}+\sum_{i=1}^{n-1}\left(\frac{lx_i-\frac{x_i^2}{2}}{\sqrt{\left(\frac{EI_i}{P}\right)^2-\left(lx_i-\frac{x_i^2}{2}\right)^2}}-\frac{lx_i-\frac{x_i^2}{2}}{\sqrt{\left(\frac{EI_{i+1}}{P}\right)^2-\left(lx_i-\frac{x_i^2}{2}\right)^2}}\right) \tag{2}$$

i : the number of node or stem from the fixed end of cantilever with continuous stages
n : a number from 1 to N, where N is the total number of node
x_i : the height from the fixed end to node i [mm]
EI_i : the flexural rigidity of stem i [N·mm^2]

EXPERIMENT AND MEASUREMENT SYSTEM

Composition of measurement system

An illustration of measurement system for deflection test is shown in Fig.2. This system is composed of markers, line-shift camera(COSMO SYSTEM, LCⅡD-5000B), image-processing apparatus(FAST, CSC901b), monochromatic monitor for positioning of line-shift camera, halogen lamps and personal computer for measuring positions of markers. Markers were made of black paper and bonded to materials. The diameter of those was 6 millimeters. The line-shift camera provides an image in two dimensions by driving CCD elements through stepping mortar. The image-processing apparatus converts an im age from camera into ones of gray tone, and then it can control range of gray tone to distinguish an object. The monochromatic monitor was used for setting initial condition of the line-shift camera and outputting results of image processing. Images of high quality were obtained by using three halogen lamps. The personal computer collects center coordinates of markers, which are recognized by image processing, through RC-232C interface.

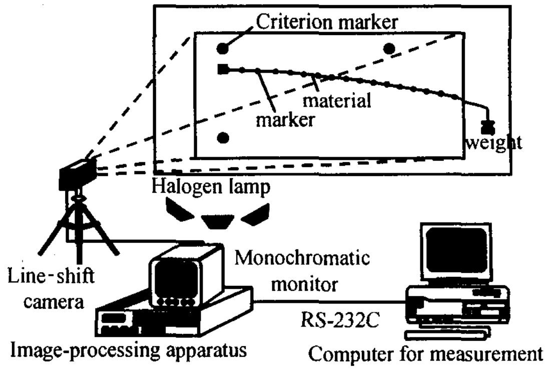

Fig.2. Illustration of measurement system for the deflection test

Measurement method

In this measurement, theory of segmentation, in which images are segmented into either white (0) or black (1), was applied in order to recognize markers digitally. Images segmented were analyzed by using program made of C language. The center coordinate of markers was calculated by geometrical moment of area of markers recognized by the image-processing apparatus. The deflection of materials was calculated by the displacement from criterion marker to each marker bonded to material and the height of those was calculated by the distance between each marker.

Experiment and materials

In this experiment, at first, deflection test of piano wire, of which EI was recognized in advance, was performed in order to inspect availability of new calculation method by Eq.(2). Next, deflection test of crop stalks (rice and wheat) as same as piano wire was performed to obtain deflection data under various loads. The load was acted on the tip of materials. While the load of piano wire was increased step by step until becoming large deflection, the load of crop stalks was arranged within the limits of deflection without destruction of stalks. In this experiment, two types of piano wire's diameter were used: 1.2 millimeters and 1.4 millimeters. Both rice stalks (MINEASAHI) and wheat stalks (CHIKUGOIZUMI) of Japonica variety used in this experiment were grown at Kyushu University Farm in Fukuoka, Japan, during 1999. Moisture contents of rice and wheat stalks were 65.9%, 55.6% on the average respectively.

CALCULATION METHOD FOR THE FLEXURAL RIGIDITY

Calculation method for the flexural rigidity by the deflection equation

By using data obtained from deflection test, EI values were calculated by the differential equation of deflection as shown in Eq.(1), (2). Integration of Eq.(1), (2) of deflection angular become ellipse function, so we cannot search generalized solution for deflection, ω. Then, deflection, ω was calculated by Runge-Kutta·Gill method, utilizing Visual Basic program. The flow chart of program for calculation of EI is shown in Fig.3. At first, measuring data, P, l, x_i, ω_i, N, which are obtained from deflection test, are inputted. Next, by using initial value of EI (EI^{ini}), deflection values (ω_i^{cal}) are calculated by numerical analysis. In this calculation, EI (EI^{ini}) is renewed repeatedly until ω_i^{cal} approach to measuring values ω_i enough. These calculations are carried out until all conditions of deflection are satisfied.

Comparison of measurement system using two equations (1), (2)

Conventional measurement system for calculation of EI values in which EI values are calculated by Eq.(1), can calculate only average EI of the whole stalk. Therefore, when EI values of crops stalk with variety sectional area are calculated, EI values of each stem divided into node have been calculated from independent condition of node, which is obtained from deflection test of each stem after the whole stalk were cut in each ones. This measurement system involves cut of stalks, so we must take exchange of markers and arrangement of camera and lighting, etc. such as required much time. These processes involve a change of moisture contents as time passes during the experiment and fatigue of crop stalks due to a few deflection test, so EI values of stalks may be not calculated accurately. On the other hand, new measurement system, which was improved by introduction of Eq.(2), can calculate EI values of each stem continuatively by each condition of node obtained from only one deflection test. Thus measuring time in new system was reduced to one-fourths of conventional system, and problems in which physical properties such as moisture contents change during the experiment, were improved.

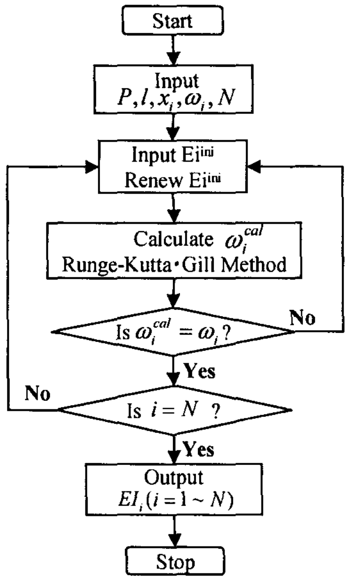

Fig.3. The flow chart of program for calculation of EI

RESULTS AND DISCUSSIONS

Calculation results of piano wire's EI

EI value of piano wire used in this experiment is constant for all sections as shown in Table 1., so it is expected to be calculated constant value even though it was calculated under the condition divided into node by Eq.(2). Then we tried to calculate EI value of

Table 1. Physical properties of piano wires

Diameter (mm)	Modulus of longitudinal elasticity (E) (N/mm^2)	Geometrical moment of inertia (I) (mm^4)	Flexural rigidity (EI) (N·mm^2)
1.2	2.1×10^5	0.102	2.142×10^4
1.4	2.1×10^5	0.189	3.969×10^4

three parts of piano wire under three conditions of node provided at equal intervals. EI of each part of piano wire was defined EI_1, EI_2, EI_3 respectively from the fixed end. Calculation results of piano wire's (diameter: 1.2mm, 1.4mm) EI, when load of 0.03(N), 0.15(N) were acted, are shown in Fig. 4 and Fig.5 respectively. Concerning calculation result as shown in Fig.4 (load:0.03N), calculated value of EI in 1.2 mm, 1.4mm piano wire had errors of 1.5~15.9%, 1.7~11.8% respectively in comparison with real EI values. On the other hand, concerning calculation result as shown in Fig.5 (load:0.15N), calculated value of EI had errors of 1.9~11.2%, 1.7~6.7% respectively; that is, it was shown that accuracy of calculation in case of large deflection (0.15N was acted) was better than that in case of small deflection (0.03N was acted). From these results, EI value calculated by using data obtained from small deflection was sensitively affected by even a tiny amount of measuring error, so EI value should be calculated by using data obtained from sufficient deflection in order to calculate EI accurately. Further, availability of calculation method of EI by Eq.(2) was shown through these results.

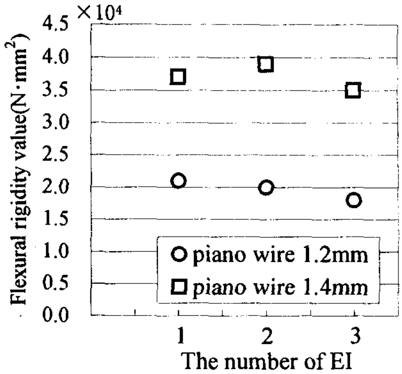

Fig. 4. Calculation result of piano wire's EI(load: 0.03N)

Calculation results of deflection of crops

Availability of calculation method of EI by Eq.(2) was shown from calculation results of piano wire's EI, so this new method was applied to crop stalks with variety sectional area. Deflection test was carried out under conditions of three varieties of load. Now, EI calculated by using data obtained from large deflection is more accuracy as mentioned above, therefore, EI was calculated by experimental data obtained from maximum load of three. After that, deflection values, when rest two loads were acted on crop stalks, were presumed by using EI calculated from maximum load. Comparisons between calculated value of deflection and actual

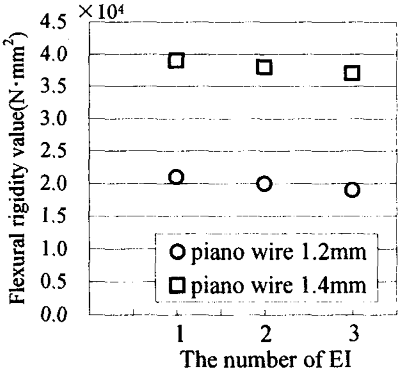

Fig. 5. Calculation result of piano wire's EI(load: 0.15N)

Table 2. Calculated value of EI of rice stalks

Average EI of the whole stalk ($N\cdot mm^2$)	EI of each stem calculated by Eq. (2) (uncut) ($N\cdot mm^2$)		EI of each stem calculated by Eq. (1) (cut) ($N\cdot mm^2$)	
2.1×10^4	EI_1	2.4×10^4	EI_1	2.0×10^4
	EI_2	1.3×10^4	EI_2	0.8×10^4

Table 3. Calculated value of EI of wheat stalks

Average EI of the whole stalk ($N\cdot mm^2$)	EI of each stem calculated by Eq. (2) (uncut) ($N\cdot mm^2$)		EI of each stem calculated by Eq. (1) (cut) ($N\cdot mm^2$)	
6.2×10^4	EI_1	5.9×10^4	EI_1	4.9×10^4
	EI_2	11.7×10^4	EI_2	8.9×10^4
	EI_3	2.8×10^4	EI_3	2.5×10^4

deflection are shown in Fig.6, 7(rice stalks) and Fig.8, 9(wheat stalks) respectively. Now, deflection was presumed by using average EI of the whole stalk calculated by Eq.(1), EI of each stem divided into node (in this case, crops are cut) calculated by Eq.(1) and EI of

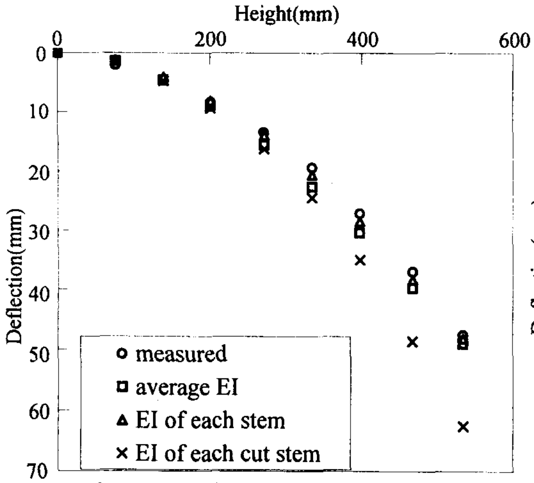

Fig.6. Calculation result of deflection of rice stalks(load: 0.02N)

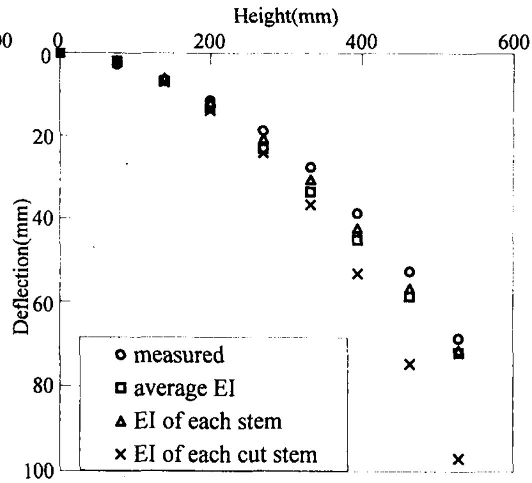

Fig.7. Calculation result of deflection of rice stalks(load: 0.03N)

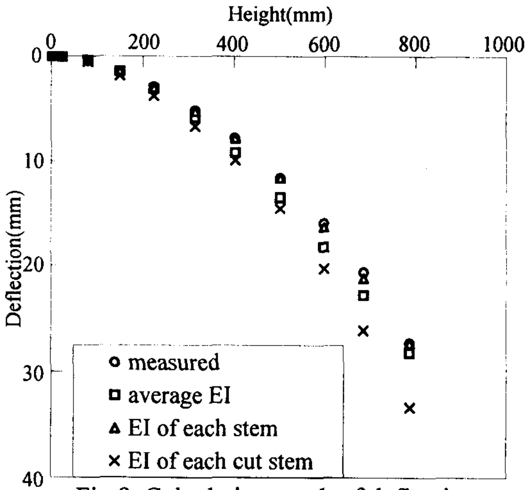

Fig.8. Calculation result of deflection of wheat stalks(load: 0.01N)

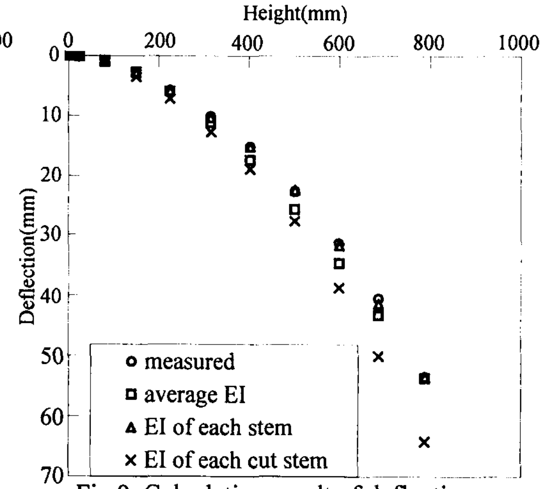

Fig.9. Calculation result of deflection of wheat stalks(load: 0.02N)

each stem (in this case, crops are not cut) by Eq.(2). The number of stem divided into node in rice stalks and wheat stalks is two and three respectively. Calculated values of EI for presuming deflection of crops are shown in Table 2. (rice stalks), 3. (wheat stalks). At first, concerning comparison results of deflection of rice stalks as shown in Fig.6 (load:0.02N), Fig.7 (load:0.03N), when deflection was presumed by using average EI of the whole stalk, predicted deflection at the acting point of deflecting forces coincided approximately with actual ones, but predicted deflection at the all point varied on the direction of height had a little errors. This phenomenon was reason because deflection of crop stalks with variety sectional area was presumed by using only average EI of the whole stalk calculated from one condition of node at tip of crops. When deflection was presumed by using EI of each stem calculated by Eq.(1), predicted deflection tended to remove from actual deflection as the point of presumption of deflection varies on the direction of height. This phenomenon was reason because crop stalks of continuous body was cut in each stem at node, which was harder part than each stem; that is, rigidity of node was not reflected to calculation value of EI, therefore small value of EI was calculated in comparison with actual EI. On the other hand, when deflection was presumed by using EI of each stem calculated by Eq.(2), predicted deflection corresponded to actual ones varied on the direction of height considerably. Next, concerning comparison results of deflection of wheat stalks as shown in Fig.8 (load:0.01N), Fig.9 (load:0.02N), predicted deflection by using EI calculated through each method had almost a tendency like rice stalks, but deflection of wheat stalks presumed by using EI of three stems coincided with actual ones more accuracy than that of rice stalks presumed by using EI of two stems. Finally, efficiency of new calculation method for EI was shown on crops with variety sectional area. Further, measuring time of deflection test was greatly reduced through this new method.

CONCLUSIONS

1) The deflection equation for crops with variety sectional area was derived, and new calculation method of EI was proposed. Further, this method was examined by using piano wire's flexural rigidity. The result has shown that in case of large deflection new method defines main characteristics of crops accurately.
2) Efficiency of new calculation method was examined on crop stalks with variety sectional area by comparison with actual deflection. As a result, deflection presumed by EI using this new calculation method corresponded with actual ones considerably.
3) Measuring time of deflection test was greatly reduced through new calculation method for EI in this study. It was implied that this new method was effective to crop stalks, which change their physical properties such as moisture contents during the experiment.

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