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THE OCCURRING FACTORS OF STANDING STEM BREAKAGE

Toshiro Nonoda[1], Setsuo Hayashi[2], Hiroshi Kawabe[3] and Yoshiaki Yonei[4]

ABSTRACT

A large number of trees showed standing stem breakage with splitting of the stem due to snow damage in the stand of sugi (*Cryptomeria japonica* D. Don.) in Mie Prefecture in December 1995. Survey of the damaged stands suggested that bending-torsional rupture caused by eccentricity of the crown was one of the factors causing stem breakage. To survey this mechanism, we applied bending and torsional loads on the stems of sugi trees. Bending without torsional stress did not cause stem breakage, but bending with torsional stress caused lengthwise splitting of the stem and stem breakage. This type of stem breakage was the same as that caused by wind and snow damages.

Key words: stem breakage, snow damage of stand, wind damage of stand

INTRODUCTION

Typical examples of meteorological damage of forest trees caused by windstorms and snow are stem breakage and tree uprooting (Kashiyama *et al*., 1971; Ishikawa *et al*. 1987). It is important to analyze the mechanism responsible for stem breakage and tree uprooting to reduce the damage of standing trees and to sustain healthy forests.

In a forest stand at Seki-cho in Mie Prefecture, stem breakage occurred due to snow damage in December 1995. The survey of this stand and previous research (Hayashi 1995) showed that stem breakage was related to the extreme slenderness of the standing trees (Yonei *et al*., 1998). Characteristic lengthwise splitting of stem was observed in the photographs of damaged forests at Seki-cho. Torsional stress may be applied in addition to the bending stress to the stem when the standing stem is broken by wind or snow, and the surface may break by both bending and torsional stresses. To examine this possibility, we surveyed the snow-damaged forest of Seki-cho again, and conducted bending and torsion tests.

1 Senior researcher, Forestry Research Division, Mie Prefectural Science and Technology Promotion Center, 3769-1 Hakusan-cho Nihongi, Ichisi-gun 515-2602, Japan (Tel.: +81-59-262-5352; Fax: +81-59-262-0960; Email: nonodt00@pref.mie.jp)
2 Professor, Faculty of Bioresources, Mie University, 1515 Kamihama-cho, Tsu, Mie Pref. 514-8507, Japan (Tel.:+81-59-231-9509 ; Fax:+81-59-231-9517; Email: hayashi@bio.mie-u.ac.jp)
3 Professor, Faculty of Agriculture, Niigata University, 8050 Igarashi Nino-machi, Niigata 950-2181, Japan (Tel.: +81-25-262-6684; Fax: +81-25-262-6684)
4 Engineer, Mie Holz, Cooperative Association of The Pole Timber Processing, 1029 Awano Iitaka-cho, Iinan-gun 515-1613, Japan (Tel.: +81-598-45-1515; Fax: +81-598-45-0398)

SNOW DAMAGE AT THE SITE OF SHOHOJISANSO-ATO IN SEKI-CHO

1. Outline of Weather and Damaged Standing Stems

One of the heaviest cold waves passed over Kameyama City, Mie Prefecture from December 24 to 28, 1995, and the forests in this area were damaged by heavy snow. With a winter monsoon pattern from December 24, the northern mass of cold air at –42 ℃ moved south over the Japan Sea and heavy snow piled from the 25th to the morning of the 27th of December in the north central region of Mie Prefecture (Meteorological observatory of Tsu district, 1995). The snow depth was 9 cm on the 26th, 45 cm on the 27th and 21 cm on the 28th. The maximum depth was attained on December 27; the average temperature of the day was 0.6 ℃ with the minimum temperature –1.7 ℃ and the maximum 3.2 ℃. Adherence of snow to the tree is considered to be strong at –3 ℃ to +3 ℃ (Ishikawa *et al*. 1987). According to the meteorological data, the weather condition at the time of snowfall at Seki-cho could be predicted to cause stem breakage by snow damage.

By the attack of the cold wave, stem breakage occurred in a part of sugi (Japanese cedar (*Cryptomeria japonica* D. Don.)) plantation at the age of 16 years, at the north central region of Mie prefecture. Fig. 1 is a photograph of the damaged stand taken six months after the occurrence of stem breakage. The characteristic lengthwise splitting of the stem is observed in this picture. This damage pattern is similar to that caused by windstorm (Hayashi *et al*. 1993). Bending and torsion seem to cause stem breakage under both heavy snow and windstorm.

Fig1: Photograph of damaged stand in the forest of Shohojisanso-ato, Seki-cho

2. The Results of The Survey of the Damaged Stand

A field survey was conducted in two sugi plantations, one damaged and the other non-damaged, to examine the characteristics of the stands at the site of Shohojisanso-ato in Seki-cho. The tree height (H), height at crown base (H_c), height of stem breakage (H_f), stem diameter at breast height (d_{120})and the percentage of broken stems were measured in July, 1996 (Yonei *et al*. 1998). Thereafter, Young's modulus was measured for the stems in damaged and non-damaged stands, four stems each, by using an instrument for the tree-bending test (Koizumi 1987, Takada 1994). Spreading of branches was measured in eight directions, and the distance of eccentricity of the crown (e) was determined as the distance from the tree base to the center of the octagon showing the spreading of the crown (Fig. 2). Simultaneously, the direction the lengthwise split plain was facing was measured with a clinometer.

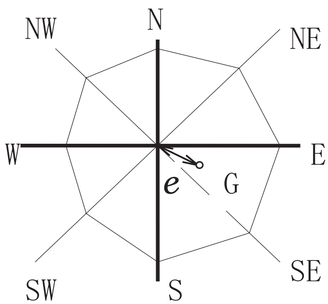

Fig2: Measurement of branch spread and the position of the center of gravity (G) on the crown. e: distance of eccentricity. G: center of gravity.

From a survey of 10m x 10m plots, the stand density was estimated to be 4900/ha and 2800/ha for the damaged and non-damaged stands, respectively, showing that the stand density of the damaged stand was much higher than that of the non-damaged stand. The percentage injury was 0% in the non-damaged stand and 33% in the damaged stand where 704 out of 864 trees in total were damaged. Furthermore, the snow-damaged stand had a high stand density and high H/d_{120} ratio, showing the structure susceptible to snow damage.

It is possible to analyze the compression stress applied to the stem by snow, as reported by Sawada (1983) and Chiba (1994). According to the analysis using Sawada's model, the smaller the H/d_{120} ratio, the larger the buckling load and the less the damage of the tree (Yonei 1998). However, the style of the stem breakage caused by snow is not attributable to the compression stress but to the splitting of the stem by the shearing stress as shown in Fig. 1. Therefore, in the present study, we examined the conditions that cause the shearing stress and stem splitting.

Fig. 3 shows the relationship between the position of the center of gravity in the crown and the direction the split plane of the stem was facing. The arrow with a broken line shows the average direction the split plane was facing and the arrow with a solid line indicates the average measured direction of the lengthwise splitting plane. The position of the ce nter of gravity of the crown was shown as the distance from the tree base. The direction of gravity of the crown from the tree base was various, although the mean direction was almost parallel to the direction the split plane of the stem was facing. The sample trees surveyed in the damaged stand were the trees left without splitting, and may not represent the characteristics of the damaged stand. However, the result showed that the eccentric load was applied in the direction the split plane was facing (SSE). The mean distance of eccentricity (e) was 13.3 cm in the non-damaged stems in the non-damaged stand and 17.1 cm in the non-damaged stems in the damaged stand. There was a tendency that the mean distance of eccentricity was slightly larger in the damaged stand than in the non-damaged stand.

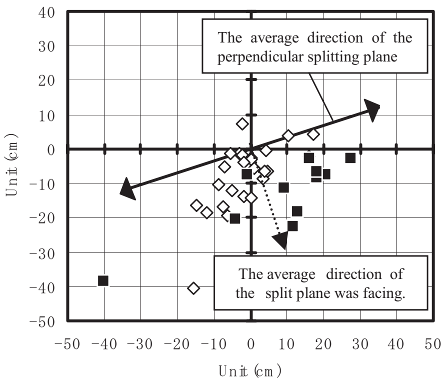

Fig3: The position of the center of gravity on the crown and the direction the lengthwise split plane of the stem.

◇: non-damaged trees in the non-damaged area

■: non-damaged trees in the damaged area

Although it is not clear whether the damaged stand had been broken by the bending and torsional stresses, it is clear that all stems were bent in the same direction in the stand. We suppose as follows. Most of the stems tended to bend in the same direction but each stem generated torsion by bending in the eccentric direction. However, because the stems are broken by this torsion, the direction the split plane was facing slightly varied from tree to tree. On the other hand, Young's modulus of stem was 6.31 MPa in the non-damaged stand, and 6.25 MPa in the damaged stand. Thus, the difference in Young's modulus between the two stands was slight, suggesting that the difference in the stem strength between the two stands ("Kumotoshi" in the damaged stand and native variety in the non-damaged stand) was not due to the varietal difference.

The survey of the forest at the site of Shohojisanso-ato is summarized as follows. The stem breakage by snow occurred in the stand with a high stand density and certain variety of sugi. Although it is important to examine the characteristics of this variety, the specificity of this variety will be examined in another occasion, and the general mechanism causing breakage of these stems was examined in the present study as reported by Ishii *et al*. (1982). Because the effects of bending and torsional stresses on stem breakage have not been examined in the previous study (Nakatani 1984, Hayashi 1995, 1998), we made the special pulling test by applying bending and torsional stresses to the stem.

BENDING AND TORSION TEST OF STANDING STEM

The conventional pulling test (Tamate 1965) and bending test (Nakatani *et al*., 1984, Kato *et al*. 1988) have been performed on the trees by bending and pulling the stems without applying torsional stress. In the present study, therefore, the effects of bending and torsional stresses were examined. The bending and torsion test was carried out in June, 1998 and November, 1998 in a 35-year-old stand in the "NI" sub-compartment of the 9th compartment at the Experimental Forest, Mie University.

1. Test Method

For the bending and torsion test, surveying instruments (transit and survey laser instrument), load-cell, data memory logger, digital camera (Cannon Eos-DCS5c, called DCS5c hereafter), winch and a loading system with lever-arm attached at a right angle to the stem were used. First, we measured the stem diameter at breast height, tree height and the crown base height. Then, Young's modulus of the standing stem was measured by using a loading system with a lever-arm attached at right angles to the stem (Hayashi 1998).

Color pins were attached to the standing stems at 1 m intervals from the point where the arm was fixed to the ground base and also at 30 cm above the ground. The plumbs were hung at 5 and 10 m height in Test Tree 5, to measure the displacement of the stem. The arm (steel bar) was attached passing through the stem center to twist the stem in Test Trees 1 and 2. The wire was bound to the arm at the surface of the stem in Test Tree 1, and at the position about 10 cm apart from the stem surface in Test Tree 2. In Test Trees 3, 4 and 5, the pipe arm, 5 cm in diameter, was fixed with a clump on the surface of the stem. The length of the arm from the center of the stem was 50 cm, and the height of each arm (loading point) was 6.0, 6.0, 7.5, 7.5 and 10.0 m in Test Trees 1, 2, 3, 4 and 5, respectively (Table 1). In Test Trees 3, 4 and 5 the twist angle of the arm was about 55°, and the direction of the arm was adjusted to make it at a right angle to the pulling direction when the stem reaches its breaking point. The torsional moment in Test Trees 1 and 2 was considered to be low due to the method of the arm attachment.

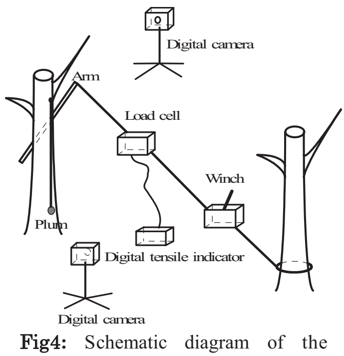

Fig4: Schematic diagram of the application of load on the stem and the position of the instruments (Test Trees 3-5)

Fig. 4 shows the method of the bending and torsion test. The wire was bound to the arm, the load-cell was set in the midst of the wire, and the other end of the wire was pulled with a winch. DCS5c was set along side the pulling stem. The measuring items were displacement of the Test Tree, the load applied on the tree, and shift of the plumb hung from the stem. The load applied on the stem was increased gradually, and was fixed transiently at each step of stem deflection. The stem fixed at each deflection step was photographed from 2 – 3 directions with the DCS5c. The shift of the plumb hung from the stem was also measured. These measurements were repeated increasing the stem-pulling load to the maximum. Some digital photographs taken with the DCS5c were transformed into three-dimensional data by using a special software (Photo Modeler Pro, called "PMP value" hereafter) and the deflection of the Test Tree was calculated.

2. Results and Discussion

(1) Results of Test

Table 1 shows the characteristics of each Test Tree and the results of the test. The Young's modulus in Test Trees 1 and 2 was lower than that in Test Trees 3 and 4. This is because Test Tree s 1 and 2 were trees planted later and younger than the other trees. Stem breakage occurred only in Test Trees 3 and 5. In Test Tree 4, uprooting occurred before stem breakage. This may be due to the soft ground. Neither stem breakage nor uprooting occurred in Test Trees 1 and 2. Test tree 1 was hardly affected by the torsional stress throughout the experimental period and did not show stem breakage. In Test Tree 2, the torsional moment was larger than in Test Tree 1, but splitting occurred at the center of the stem where the lever arm was fixed, and not at the bent part of the stem. It is considered that stem breakage did not occur in Test Trees 1 and 2 because of the shortage of torsional momentum due to defectiveness of the experimental method, although Young's modulus was also low in these trees. Tamate *et al*. (1965) indicated that pulling of the standing tree without torsional stress caused uprooting scarcely causing stem breakage. This was also the case in our test.

Tab.1: Results of bending and torsion test by pulling down the trees, diameter of breast height (d_{120}), height to base of crowns (H_C), tree height (H), height of stem breakage points (H_f), height of loading points (L), Young's modulus of the stems (E) and the maximum load (P_{LM}).

Trees	d_{120} (cm)	H_C (cm)	H (cm)	H_f (cm)	L (cm)	E (MPa)	P_{LM} (kN)	State of the tree
1	14.9	382	1126		600	3.69	1.50	No stem breakage
2	16.2	455	1382		600	4.76	1.93	Splitting by defective stem
3	15.6	780	1785	235	750	10.40	1.44	Stem breakage
4	15.3	714	1604		750	7.78	1.17	Tree uprooting
5	16.9	1175	1742	308	1000	6.75	1.65	Stem breakage

Fig. 5(a) shows a photograph of Test Tree 3 just before stem breakage occurred. The stem was broken by splitting at the center of the stem in the pulled direction, and the stem fell down gradually. At the top of the broken tree, the stem was torn along the direction of lengthwise fibers.

Fig. 5(b) is the photograph of the basal part of the broken tree. Lengthwise splitting along the center of the stem is observed in this photograph. Compression failure was also observed at the part subjected to compression force. Test tree 3 broke at the height of 235cm, and had lengthwise splitting at the center of the stem, as in the trees damaged by windstorm or snow.

By applying bending and torsional stresses to the stem, lengthwise shearing stress may be given to the stem surface (Yanagisawa *et al*. 1986), causing stem breakage. The stem of test tree 3 broke at a lower position than the trees damaged by snow and others, but this is merely because the loading point was low in Test Tree 3.

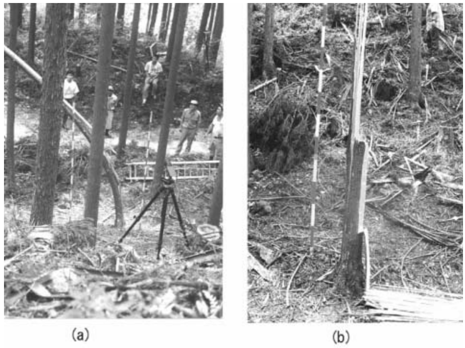

Fig5: Photograph of stem breakage (Test Tree 3)

(2) Relationship Between Horizontal Deflection and Load Applied on The Test Trees

Fig. 6 shows the relationship between the horizontal deflection and the load applied to Test Tree 3. In this figure, values in parentheses are the height of attached color pins used for PMP analysis. The values at each height were analyzed using PMP. Some abnormal values due to analyzing error are included in this graph. The broken lines in this graph show the relationship between the horizontal deflection and the load eliminating these abnormal values. At first, the horizontal deflection increased with increasing load. After the load reached a peak, the horizontal deflection increased accompanied with a slight decrease in the load. The peak load was 1.44 kN. At this time, the deflection was 24 cm at the stem height of 350cm, and 80cm at the stem height of 750cm. The large variation in the “PMP values” may be attributed to the small number of photographs and small horizontal angle between each camera. In Test Tree 5, splitting was observed at the center of the stem as shown in Fig. 5 for Test Tree 3. Test tree 5 broke at the height of 308cm, but did not tear along the lengthwise fibers so severely as in Test Tree 3. Test tree 5 broke at a higher position than Test Tree 3, because the loading point (1,000cm) in Test Tree 5 was higher than that (750cm) in Test Tree 3.

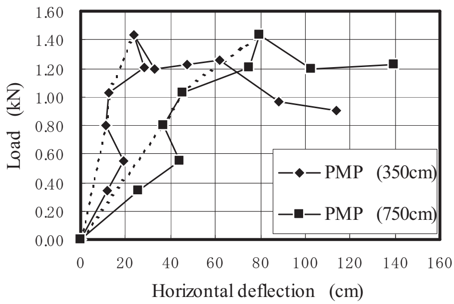

Fig6: Relationship between horizontal deflection and the pulling load (Test Tree 3).

Fig. 7 shows the relationship between the horizontal deflection and the pulling load. In this figure, “measured value” shows the shifted distance of the hung plumb. In Test Tree 5, the peak of the load was 1.65 kN, and at this point, the horizontal deflection was 88cm in “measured value”, and 75cm in “PMP value” at the height of 500cm. The deflection at the loading point was 282cm in “measured value” and 268cm in “PMP value”. The difference between “measured value” and “PMP value” was the maximum at 0.98kN load, and the difference was 34 cm. In Fig. 7, the horizontal deflection increased slightly until the load reached a peak, and increased further accompanied with slight decrease in the load. This phenomenon is the same as in Test Tree 3. In these trees, elastic deflection proceeded with increasing load, and then plastic deflection due to internal destruction of the stem proceeded resulting in the decrease in the load.

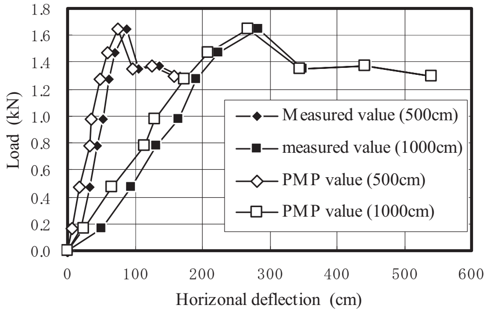

Fig7: Relationship between horizontal deflection and pulling load (Test tree 5).

Although the deflection process in Test Tree 5 was almost the same as that in Test Tree 3, the accuracy of "PMP value" in the former was higher than that in the latter. In Test Tree 5, the difference between "measured value" and "PMP value" for the horizontal deflection was 13cm on the average. The "PMP value" in Test Tree 5 was more accurate than in Test Tree 3, probably because more photographs were analyzed. The "PMP value" may be useful for evaluation without actual measurement.

The results of this test are summarized as follows. In Test Trees 1 and 2, which were bent by pulling without torsion, neither stem breakage nor lengthwise splitting of the stem occurred. On the other hand, in Test Trees 3 and 5, which were bent by pulling with torsion, stem breakage with lengthwise splitting of the stem occurred. The results suggest that the stem breakage in Test Trees 3 and 5 occurred in the same pattern as that due to damage by snow and windstorm.

(3) Interpretation of The Test Result in Tamate *et al* (1965)

Tamate *et al* (1965) carried out the pulling tree test in 17 examples, which inclueded the sugi tree (*Cryptomeria japonica D.Don.*) and a number of other tree species. The test is a method of pulling the tree in an oblique downward direction simply by the wire on the tree stem, and torsional force does not act to the conifer. The load points height are 5.1m～8.5m, and so they are not different from the present test. In this test, the test trees with stem breakage occurred in 5 examples, tree uprooting occurred in 11 examples, and the 1 remaining example was splitting at the stem. The consideration of Tamate *et al* (1965) in the 5 examples with stem breakage is as follows. 3 out of the 5 examples had fungus injury in the inside anyway, and stem breakage occurred at every damaged position of these trees. The remaining 2 examples (tree No.17 and No.9) in which stem breakage occurred were the sound trees, No.17 akamatu (*Pinus densiflora SIEB. E$_{T\ ZUCC}$.*) broke its stem similar to the shear. With No.17 akamatu, applying the test position at the soil seems to be stronger than any other place.

From the test results of Tamate *et al* (1965) in 17 examples, stem breakage occurred only in 2 examples with the exception of the fungus injury trees. The cause of stem breakage in these 2 examples will be considered as the following. The stem breakage of tree No.17 akamatu occurred by the shear. Though there was no given reason why stem breakage occurred in No.9 arakashi tree (*Quercus acuta T$_{HUNB}$.*), arakashi is a broad-leaved tree, and there is a great possibility for stem breakage at the position of the knot. In the 8 examples of the conifer of sugi and hinoki (*Chamaecyparis obtusa E$_{NDL}$.*), the tree uprooting occurred in 7 examples, and the 1 example with the stem breakage was in a fungus injury tree. From the test results of Tamate *et al* (1965), it is possible to consider that these stem breakages do not occur at least in the simple pulling test of sugi and hinoki with sound conifer. On this fact, it means that the stem breakage does not occur with the splitting, when the shear force does not act on the stem surface by some cause. Therefore, it is difficult to consider the cause except torsional forces acted on the stem for the stem breakage occurrence with the splitting in this case.

From the results and the consideration above (1) ～ (3), the effect of the pulling tree tests led to the following points . To begin with, the result of our test tree 1 and test tree 2, where stem breakage did not occur, only acted the bending force by almost pulling the trees, and these test trees did not generate lengthwise splitting on the stem. In addition, on our test tree 3 and test tree 5 in which stem breakage did, both test trees generated lengthwise splitting. From these, it is considered that the stem breakage in present test results generate the shear destruction on the stem surface by the torsion at the beginning, which is a similar situation to an actual stem breakage damaged tree, that would result in the destruction of the stem.

CONCLUSION

In this study, the bending and torsion test was conducted to elucidate the mechanism of stem breakage of sugi tree, Japanese cedar (*Cryptomeria japonica D. Don.*), as an example of forest damage, and the results were discussed.

The survey of the sugi stand at the site of Shohojisanso-ato damaged by snow in December, 1995, showed that the trees in the damaged stand were taller and had smaller average stem diameter at breast height than those in the non-damaged stand. These results suggested that the trees in the damaged stand were apt to bend easily. However, lengthwise stem splitting was clearly observed in the damaged trees in the stand. We considered that when stem breakage occurs, torsional stress caused by eccentric load of the crown was applied to the stem in addition to bending stress, resulting in the lengthwise splitting. Therefore, to clarify the relationship between the occurrence of splitting and eccentric load of the crown, we examined the relationship between the position of the center of gravity of the crown and the direction of the lengthwise split plane of the stem. The results showed that the center of gravity of the crown of damaged tree was usually positioned in the same direction as the duration the split plane was facing. This suggests that the torsion stress affected the occurrence of the stem splitting.

To examine whether the stem breakage occurs when torsional stress is applied, we applied the bending stress to the stem by pulling, and simultaneously applied torsional stress to break the stem. Stem breakage did not occur in the trees to which bending stress was applied without torsional stress. On the other hand, in the trees to which bending stress was applied together with torsional stress, stem breakage with lengthwise splitting occurred as in the stems damaged by windstorm and snow.

In conclusion, the torsional moment plays an important role in the occurrence of the breakage. The stems of the trees under windstorm or snow may scarcely bend without torsion. If torsional stress is applied to the stem by some factors together with bending stress, stem breakage may occur from the stem surface. Studies on the effect of internal stress on the breakage of the stem from the surface are underway.

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