# Survey of Typhoon-Damaged Coniferous Forests and Strength Properties of Lumber and Glued Laminated Timber Processed from Damaged Japanese Cedar and Japanese Cypress Trees

Isao Toyoshima
Hiroshi Noguchi
Mariko Yamasaki
Yasutoshi Sasaki

## Abstract

Typhoon Melor, which occurred in October 2009, damaged much of the forest in the eastern region of Japan's Aichi Prefecture. The damaged trees were primarily planted Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*) between 40 and 60 years old and were intended for use as structural lumber. The purpose of this study was to investigate the usability of damaged trees for structural lumber. First, the state of the damaged forests was assessed, and the occurrence of compression failure (CF) in logs and lumber from damaged trees was surveyed. The strength properties of the lumber and glued laminated timber of both species were then determined, and usage-related issues for each species were investigated. The study found that the majority of damaged forests had a high stand density and indicated a high diameter at breast height–to–height ratio. The most common damage type was *overturned*. The rate of CF occurrence in damaged logs and lumber from damaged trees, in logs with the bark on, was highest in those that had suffered from *bending*. For lumber, the rate was highest in *inclined* and *bending* cases, and there were also a few instances in *overturned* cases. In lumber from damaged trees, a higher Young's modulus was slightly associated with a higher rate of CF occurrence. In terms of the strength properties of lumber from damaged trees, lumber in which the postprocessing surface showed no CF exceeded the standard strength for both species. The properties of lumber in which minute CF was visible on the surface were similar to lumber without CF for Japanese cedar, but Japanese cypress lumber with visible CF exhibited a failure morphology that failed within the elastic range, and most specimens fell short of standard strength. In addition, laminae cut from damaged trees were processed into glued laminated timber, using laminae on which CF could not be seen on the surface. These bending properties were compared with those of glued laminated timber processed from laminae made from normal trees. This comparison showed that the strength of both was similar in the Japanese cedar, whereas in the Japanese cypress, the bending strength (modulus of rupture) of the damaged glued laminated timber was significantly lower than that of normal trees.

In Japan, forests are frequently at risk of wind damage from typhoons that hit the Japanese archipelago numerous times each year. Aichi Prefecture was hit by Typhoon Melor in October 2009, which damaged a large number of planted coniferous forests. Currently, Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa*) make up the largest area of planted forests in Japan. These trees are between 40 and 60 years old and have been

The authors are, respectively, Senior Researcher, Aichi Prefectural Forest and Forestry Research Inst., Shinshiro, Japan (isao_toyoshima@pref.aichi.lg.jp); Director, Aichi Prefectural Toyota-Kamo Agric., Forestry, and Fisheries Office, Toyota, Japan (hiroshi_noguchi@pref.aichi.lg.jp); and Associate Professor and Professor, Dept. of Biosphere Resource, Graduate School of Bioagricultural Sci., Nagoya Univ., Nagoya, Japan (marikoy@agr.nagoya-u.ac.jp [corresponding author], ysasaki@nagoya-u.jp). This paper was received for publication in September 2016. Article no. 16-00052.

Forest Prod. J. 68(1):25–36.
doi:10.13073/FPJ-D-16-00052

planted since the 1950s as part of national afforestation policies. Planted forests of this age have an increased ratio of diameter at breast height to height (DBH-H), and the trees have a high center of gravity, so they are susceptible to wind damage from typhoons (Fujimori 1995). Furthermore, since the price of lumber has been suffering from long-term stagnation, planted forests that are not yielding profits for forestry have not been subject to the routine thinning necessary to encourage healthy forests. It has been found that the stand density and DBH-H ratio of such forests increases, and then their structure weakens against wind pressure (Isamoto and Takamiya 1992). In addition, there were many studies on the damage by hurricanes in the United States. Reilly (1991) suggested the taller and larger-diameter trees are more severely damaged than shorter and smaller-diameter trees. In addition, Gresham et al. (1991) found that the amount and nature of wind damage differed among the tree species. Faust et al. (1994) found that specific gravity among pine pole timber influenced the damage level. Thus, the factor of the degree of damage by high wind is complicated.

It is predicted that with the climate change that accompanies global warming, even stronger typhoons will affect Japan in the future (Tsuboki et al. 2015). Therefore, making the efficient use of wind-damaged trees is becoming an important issue. According to Ruel et al. (2010), the longer the time since damage occurred, the less the value of the products from the damaged trees. Therefore, it is necessary to carry out the damaged trees rapidly. In addition, wood obtained from wind-damaged trees is thought to be of lower quality due to internal structural damage. Because the trunks of wind-damaged trees have been repeatedly bent by strong winds, compression failure (CF) can occur (Miyajima 1959, Fujimoto et al. 1995, Arnold 2003). CF forms wrinkle-like compression marks that appear transverse to the trunk. The size of these marks varies from being clearly visible on the surface of the bark to minute deformations of cell walls (Kord 2007). For this reason, it is difficult to fully detect minor CF at the rough-sawn lumber stage (Arnold 2003). Many studies have investigated the effects of CF on the strength properties of lumber. Arnold and Steiger (2006) conducted full-scale bending tests using lumber from wind-damaged spruce and compared the strength properties of lumber with CF visible to the naked eye with those of lumber without CF. The former had a clearly lower bending strength (modulus of rupture [MOR]). In addition, Matsumura et al. (1993) took small specimens close to the bark of damaged logs of Japanese cedar and Japanese cypress and compared the bending properties of the CF side of the log with those of the opposite side. They found that the CF-side specimens had a lower modulus of elasticity (MOE) and MOR regardless of whether there was visible CF on the specimen surface. On the other hand, when Kokura et al. (1993) conducted a full-scale bending test of lumber from damaged Japanese cedar with CF on the bark and compared this with lumber taken from normal trees, they found no significant difference. The effects of CF on mechanical properties are thus thought to differ between tree species and specimen size and according to the degree of CF.

Given the above, this study surveyed the damage to Japanese cedar and Japanese cypress forests caused by Typhoon Melor in Aichi Prefecture in October 2009 and considered the effective use of such wind-damaged trees. The study first surveyed the state of damaged forest and CF occurrence in damaged logs and lumber from damaged trees. Full-scale bending tests were then performed on lumber and glued laminated timber to investigate the potential for its use for structural purposes.

## Materials and Methods

### Survey of damaged planted forests

As shown in Figure 1a, the part of Aichi Prefecture that was most affected by Typhoon Melor was the suburbs of Shinshiro City. Twenty-nine sites were surveyed in this region (Fig. 1b). At each survey site, a 10 by 10-m plot with a typical amount of damage was established (Fig. 2). Within each plot, forest age, stand density (number of standing trees and number of fallen trees), DBH, elevation, orientation,

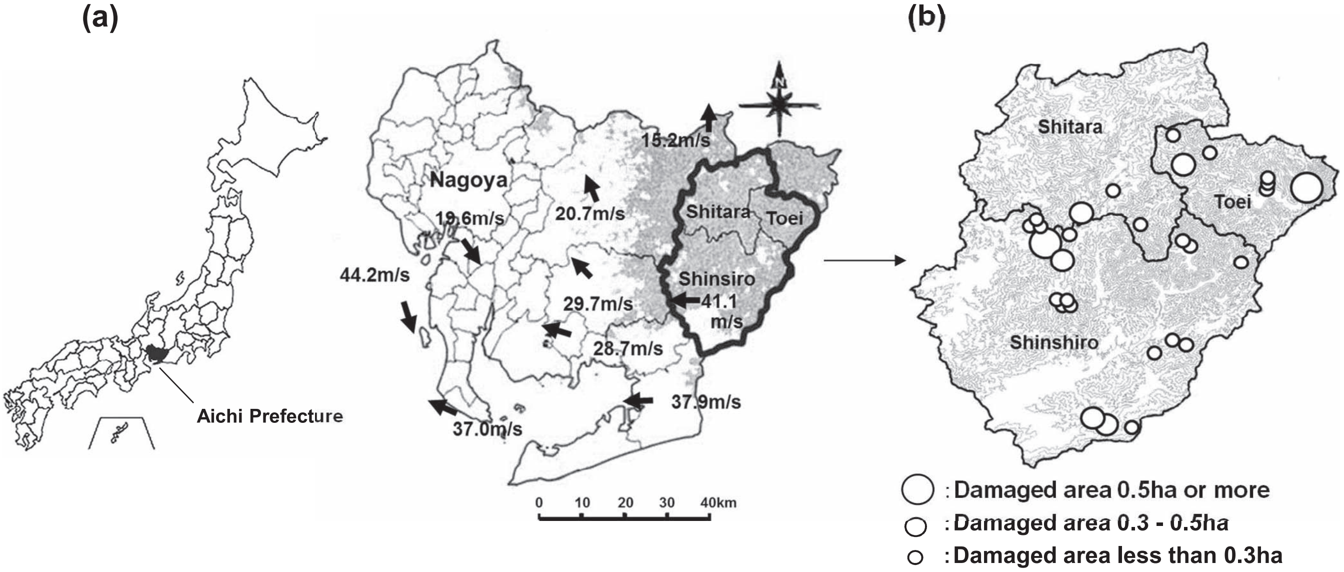

*Figure 1.—Maximum instantaneous wind speed in Aichi Prefecture and surveyed sites. (a) Gray shaded areas show the distribution of planted Japanese cedar and Japanese cypress forests. (b) Circles show the sites within the damaged areas that were surveyed.*

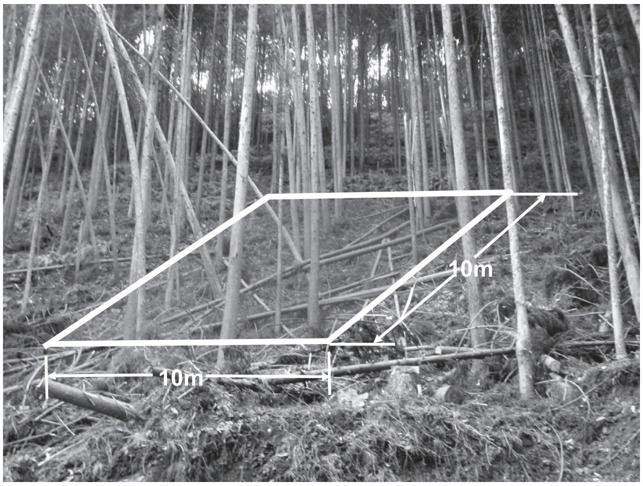

Figure 2.—Example of a survey plot.

slope, and damage type were surveyed. Table 1 shows detail of the surveyed forests. As shown in Figure 3, damage type was divided into five categories: *overturned* (toppled from the roots), *bending* (bowed trunk), *inclined* (tilted trunk), *snapped* (broken at some point along the trunk), and *outwardly undamaged* (standing straight with no visible damage). A total of 276 trees were surveyed across the sites. As shown in Figure 1, the maximum instantaneous wind speed of the typhoon in Shinshiro City was 41.1 m/s, and the wind direction was easterly (Nagoya Meteorological Observatory 2009). This was the highest wind speed recorded in planted forests in Aichi Prefecture.

## Test material

Damaged trees were removed from five damaged forests in 2012 and 2013. The number and species of standing trees, fallen trees, and logs used in the experiment is summarized according to damage type in Table 2. The top diameter of the Japanese cedar logs was 18.6 ± 4.1 cm (mean ± SD), and that of the Japanese cypress logs was 18.0 ± 4.0 cm. From the logs, lumber specimens were sawed as close as possible to the measurements 110 by 110 by 3,000 mm or 125 by 125 by 3,000 mm. The logs used to make laminae were sawed to 115 by 25 by 3,000 mm for Japanese cedar and 115 by 25 by 4,000 mm for Japanese cypress, yielding 125 laminae of Japanese cedar and 96 laminae of Japanese cypress. After being dried to equilibrium moisture content (MC), these were planed to 105 by 105 by 3,000 mm or 120 by 120 by 3,000 mm for the lumber and 110 by 21 by 3,000 mm for the laminae of Japanese cedar and 110 by 21 by 4,000 mm for the laminae of Japanese cypress.

## Survey of CF in damaged logs and in lumber from damaged trees

The surface of the logs was visually inspected, with the bark on, for signs of CF. The surface of the planed lumber was then visually surveyed for CF (Fig. 4), and the relationship between damage type and rate of CF occurrence was assessed. The dynamic Young's modulus of the lumber was also measured, using the longitudinal vibration method, and its relationship with rate of CF occurrence was assessed.

## Full-scale lumber bending test

A full-scale bending test was conducted on the lumber, and the MOE and MOR were measured. A total of 66 specimens were tested (49 Japanese cedar and 17 Japanese cypress); the presence of CF is summarized in Table 3. CF was assessed according to Arnold and Steiger's (2006) definition. That is, CF was defined as minute defects of $<0.5$ mm in axial width, which can normally be seen with corrected vision. Two to three of these defects were observed on the lumber surface of each sample. Table 4 shows the density at 15 percent MC of the lumber. The density of the lumber without CF and with CF did not differ from each other ($P = 0.15$ for Japanese cedar, $P = 0.33$ for Japanese cypress). In terms of the loading method, a four-point bending test with a span of 2,700 mm was conducted at a deflection speed of 20 mm/min. After the test, two 20-mm-thick test pieces were cut from each specimen, each taken 1 m from respective ends of the specimen, and the MC at the time of the experiment was measured, using the ovendrying method.

## Full-scale glued laminated timber bending test

Of the laminae from damaged trees, specimens on which CF was not observed on the surface were used to produce five-ply glued laminated timber of equal grade (hereafter, damaged glued laminated timber), based on Japanese Agricultural Standards (JAS). The specimen size was 105 by 105 by 3,000 mm for Japanese cedar and 105 by 105 by 4,000 mm for Japanese cypress. The longitudinal vibration method was used to determine the grade of the lamina, based on Young's modulus. According to JAS, the grade of the glued laminated timber was determined as E65 when Young's modulus was 6.5 to 7.5 kN/mm$^2$, E75 when it was 7.5 to 8.5 kN/mm$^2$, E85 when it was 8.5 to 9.5 kN/mm$^2$, E95 when it was 9.5 to 10.5 kN/mm$^2$, E105 when it was 10.5 to 12.0 kN/mm$^2$, E120 when it was 12.0 to 13.5 kN/mm$^2$, and E135 when it was 13.5 to 15.0 kN/mm$^2$. In order to evaluate the strength properties of this damaged glued laminated timber, they were compared with those of five-ply glued laminated timber of equal grade produced from laminae obtained from forests that were not affected by a typhoon

Table 1.—Details of the surveyed forests.

| | Unit | Mean | SD | Max. | Min. |
|---|---|---|---|---|---|
| Forest age | Years | 49 | 9 | 80 | 36 |
| Stand density | ha$^{-1}$ | 1,190 | 410 | 2,400 | 600 |
| | ×0.01 ha$^{-1}$ | 12 | 4 | 24 | 6 |
| Diameter at breast height | cm | 25 | 4 | 32 | 20 |
| Elevation | m | 312 | 150 | 650 | 110 |
| Orientation | Degrees | 114 | 85 | 342 | 18 |
| Slope | Degrees | 32 | 20 | 50 | 0 |

***Overturned*** ***Inclined***

***Bending*** ***Snapped***

*Figure 3.—Damage type categories.*

(hereafter, normal glued laminated timber). As shown in Table 5, the numbers of test specimens were as follows: 10 Japanese cedar and 15 Japanese cypress specimens for damaged glued laminated timber and 16 Japanese cedar and 36 Japanese cypress specimens for normal glued laminated timber. The density at 15 percent MC of specimens is shown in Table 4. The density of the normal and damaged glued laminated timbers did not differ from each other ($P = 0.59$ for Japanese cedar). For both groups, because the rim knot size influenced the MOR, laminae were used only when they had the largest rim knot of the outermost layer covering $\leq 25$ percent of the lumber width according to JAS visual Grade 2. The adhesive used was aqueous vinyl urethane–based adhesive (AU-7300FL). The production conditions were a compressive pressure of 7 to 8 kg/cm$^2$ over 8 hours. A full-scale bending test was conducted on the glued laminated timber to measure the MOE and MOR. In terms of the loading method, spans of 2,700 mm for the Japanese cedar and 3,600 mm for the Japanese cypress were used, and the four-point bending test was conducted at a deflection speed of 20 mm/min. After the test, two 20-mm-thick test pieces were cut from each specimen, each taken 1 m from respective ends of the specimen, and the MC at the time of the experiment was measured using the ovendrying method.

## Results and Discussion

### Survey of damaged planted forests

Figure 5 shows the relationship between stand density and average DBH of the 29 forest sites surveyed. The curved line is the wind and snow damage boundary line, as proposed by Ogaya (2002). This is the line where the total basal area of standing trees is 50 m$^2$/ha. The forests above this line have a DBH-H ratio of >70 and are considered to have a high risk of wind and snow damage. As shown in

*Table 2.—Details of the specimens taken from damaged forest survey sites.*[a]

| Species | Specimen type | Total no. of trees (no. of logs) | No. of trees (no. of logs) for each damage type: Overturned | Bending | Snapped | Inclined | Outwardly undamaged |
|---|---|---|---|---|---|---|---|
| Japanese cedar | Lumber | 25 (49) | 16 (34) | 6 (8) | | 2 (4) | 1 (3) |
| | GL timber | 9 (18) | | 5 (10) | | 4 (8) | |
| | Total | 34 (67) | 16 (34) | 11 (18) | | 6 (12) | 1 (3) |
| Japanese cypress | Lumber | 15 (17) | 11 (11) | 4 (6) | | | |
| | GL timber | 7 (15) | | 2 (5) | | 5 (10) | |
| | Total | 22 (32) | 11 (11) | 6 (11) | | 5 (10) | |

[a] GL = glued laminated.

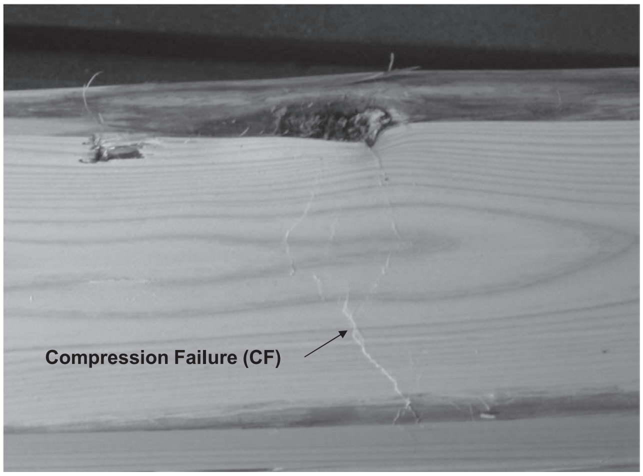

*Figure 4.—Compression failure (CF) on the surface of a lumber specimen.*

Figure 5, 22 plots fell above this line. In other words, approximately 70 percent of the surveyed sites had a high stand density and had what is considered to be a high DBH-H ratio. Figure 6 gives the proportion of each damage type at the 29 surveyed sites. Overturned was the most common damage type, comprising approximately 60 percent of the total.

The other damage types (bending, snapped, and inclined) each made up 5 to 10 percent of surveyed trees and outwardly undamaged about 20 percent. Many of the outwardly undamaged trees were situated at the forest edge, where they received good sunlight, had a low DBH-H ratio, and may have had well-developed root systems.

## Survey of CF in damaged logs and in lumber from damaged trees

The surfaces of logs with the bark attached and of lumber were observed with the naked eye. Figure 7 shows the rate of CF occurrence according to damage type. The total for

*Table 3.—Details of lumber specimens.*[a]

| Species | Presence of CF | $n$ | Mean (SD) MOE (kN/mm$^2$) | Mean (SD) MOR (N/mm$^2$) |
|---|---|---|---|---|
| Japanese cedar | Without[b] | 43 | 8.4 (1.2) | 45.4 (7.7) |
| | With[c] | 6 | 8.9 (1.4) | 51.0 (6.0) |
| Japanese cypress | Without | 12 | 9.8 (1.1) | 48.7 (10.1) |
| | With | 5 | 10.2 (1.4) | 32.2 (10.2) |

[a] CF = compression failure; MOE = modulus of elasticity; MOR = modulus of rupture.

[b] Without = CF was not visible with the naked eye under normal conditions.

[c] With = CF can normally be seen with corrected vision. Number of CF: a few; width of CF: fine.

*Table 4.—Density at 15 percent moisture content and the moisture content at bending test for lumber and glued laminated (GL) timber.*

| Specimen type | Species | Condition | $n$ | Mean (SD) Density ($\rho_{15}$) (kg/m$^3$) | Mean (SD) Moisture content (%) |
|---|---|---|---|---|---|
| Lumber | Japanese cedar | Without CF[a] | 43 | 397 (30) | 15.6 (2.0) |
| | | With CF[b] | 6 | 416 (26) | 13.9 (0.3) |
| | Japanese cypress | Without CF | 12 | 534 (40) | 14.4 (0.9) |
| | | With CF | 5 | 513 (38) | 13.9 (0.4) |
| GL timber | Japanese cedar | Normal[c] | 16 | 393 (13) | 12.0 (0.8) |
| | | Damaged[d] | 10 | 398 (32) | 12.4 (1.0) |
| | Japanese cypress | Normal | 36 | 515 (26) | 14.4 (1.0) |
| | | Damaged | 15 | 502 (28) | 13.9 (1.1) |

[a] Without CF = compression failure (CF) was not visible with the naked eye under normal conditions.

[b] With CF = CF can normally be seen with corrected vision. Number of CF: a few; width of CF: fine.

[c] Normal = glued laminated timber from forests that was not affected by a typhoon.

[d] Damaged = glued laminated timber from damaged trees was made only from laminae in which CF was not visible with the naked eye under normal conditions.

*Table 5.—Details of glued laminated timber bending specimens from normal and damaged trees.*

| | | No. of trees for each grade (Young's modulus in kN/mm$^2$) | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Species | Condition | E65 (6.5–7.5) | E75 (7.5–8.5) | E85 (8.5–9.5) | E95 (9.5–10.5) | E105 (10.5–12.0) | E120 (12.0–13.5) | E135 (13.5–15.0) |
| Japanese cedar | Normal[a] | 3 | 6 | 5 | 2 | | | |
| | Damaged[b] | 1 | 3 | 2 | 3 | 1 | | |
| Japanese cypress | Normal | | | 5 | 6 | 9 | 12 | 4 |
| | Damaged | | | 2 | 2 | 5 | 4 | 2 |

[a] Normal = glued laminated timber from forests that was not affected by a typhoon.

[b] Damaged = glued laminated timber from damaged trees was made only from laminae in which compression failure was not visible with the naked eye under normal conditions.

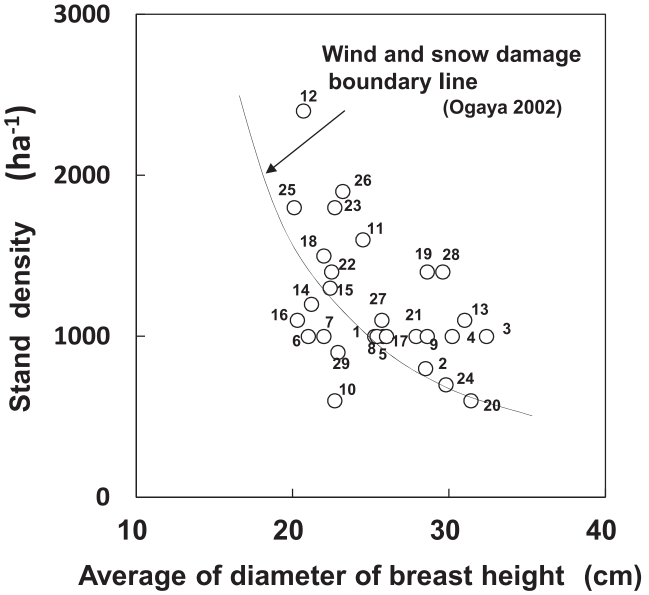

*Figure 5.—Relationship between average diameter at breast height and stand density at survey sites. Sites above the wind and snow damage boundary line (dotted line) show that the risk of wind and snow damage is high.*

the two species is shown. For the logs of both species, the rate of CF occurrence was highest for those that had suffered from bending, followed by those that were inclined. No CF was observed for those that were overturned or outwardly undamaged. For the lumber, the rates of CF occurrence for inclined for Japanese cedar was high, at 50 percent and bending trees for both species were at approximately 40 percent, and was low (<30%) for overturned for both species. Next, Figure 8 shows the relationship between the dynamic Young's modulus and rate of CF occurrence for the lumber. The lumber surveyed was divided into two groups: lumber with a Young's modulus below (Group 1) or above (Group 2) the median (8.2 kN/mm$^2$ for Japanese cedar and 10.0 kN/mm$^2$ for Japanese cypress). The rate of CF occurrence in Group 1 Japanese cedar was 8 percent, while that in Group 2 was 17 percent. For the Japanese cypress, this rate was 22 percent for Group 1 and 38 percent for Group 2. Thus, for both species, the group with the higher dynamic Young's modulus had a slightly higher rate of CF occurrence. Midori et al. (1992) found that the rate of CF occurrence differed between varieties of Japanese cedar and was generally high for trees with a high Young's modulus. They observed that the variety *Kumotooshi*, which had a high rate of CF, also had a relatively high Young's modulus of 7.3 GPa (average), while the variety *Ayasugi*, which had a low rate of CF, had a lower Young's modulus of under 5.6 GPa. In other words, this indicates that trees with a high Young's modulus may not necessarily have low CF occurrence from the perspective of forest management.

## Full-scale bending properties of lumber from damaged trees

Figures 9a and 9b show the load-deflection curves for the lumber from damaged trees of Japanese cedar and of Japanese cypress, respectively. Thin lines represent specimens without CF and thick lines those with CF. It seems that the deflection of the lumber with CF differs from that

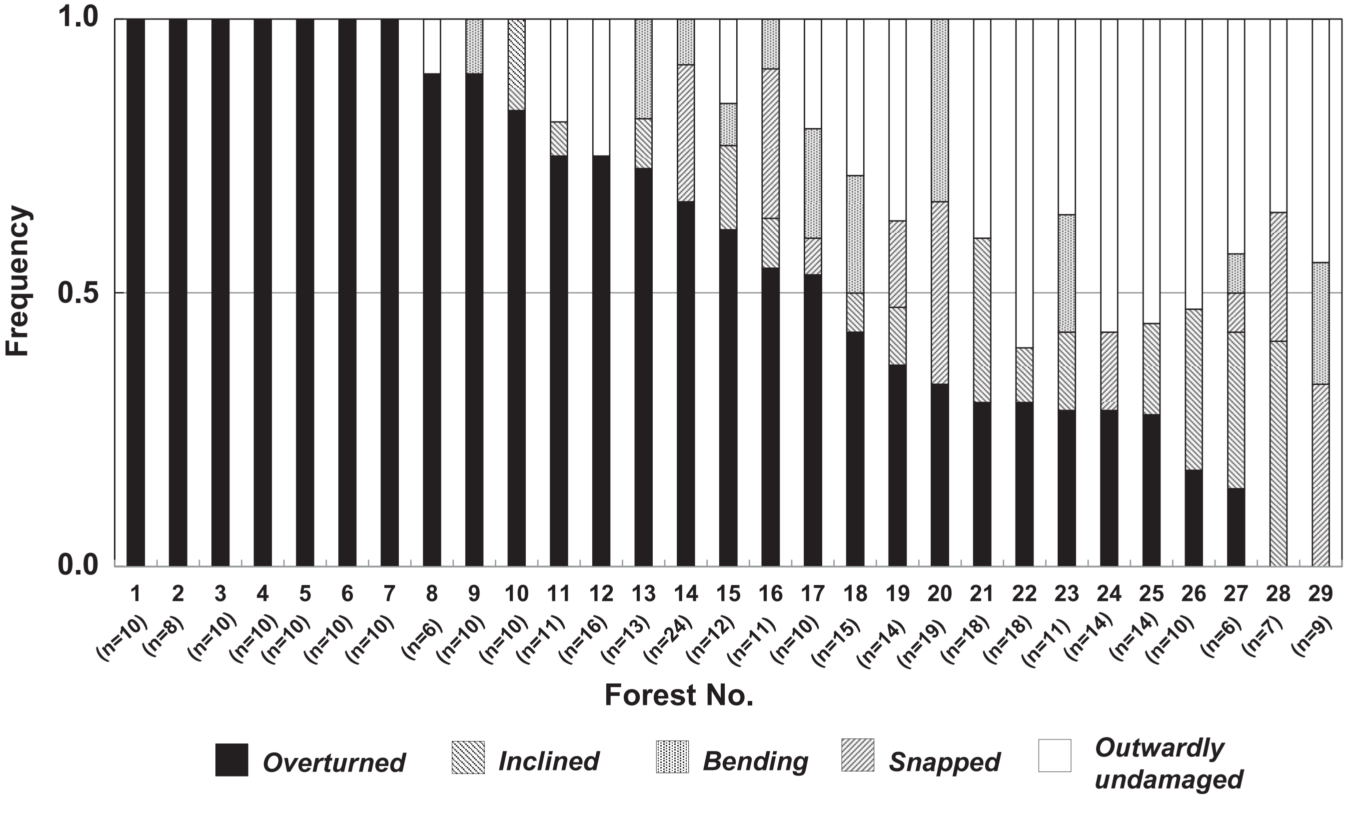

*Figure 6.—Damage type composition of surveyed forests.* n = *number of standing and fallen trees in surveyed forest plots.*

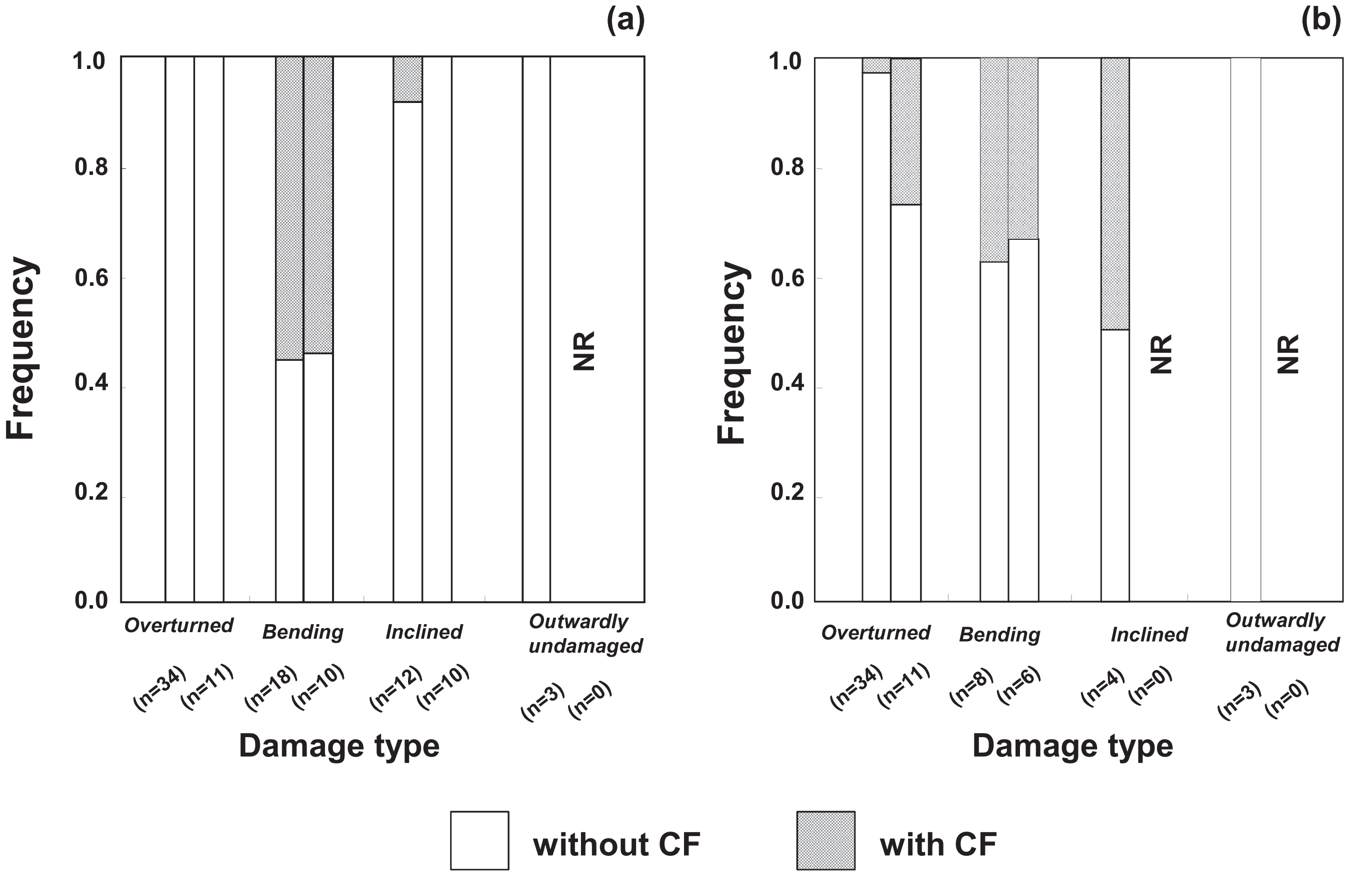

*Figure 7.—Comparison of rate of compression failure (CF) occurrence between damage types in (a) logs and (b) lumber. Left of bar graph paired: Japanese cedar; right of bar graph paired: Japanese cypress. NR = data not reported.*

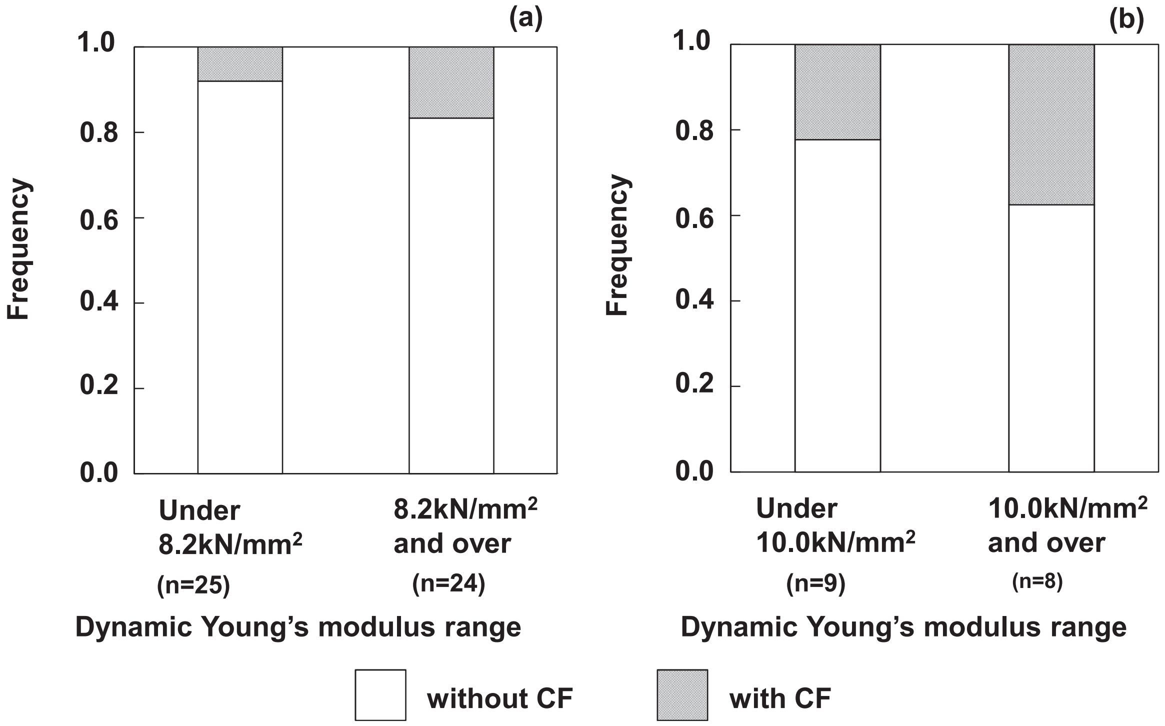

*Figure 8.—Comparison of rate of compression failure (CF) occurrence in lumber with high and low dynamic Young's modulus of (a) Japanese cedar and (b) Japanese cypress. Median dynamic Young's modulus of Japanese cedar specimens is 8.2 kN/mm$^2$ and of Japanese cypress specimens is 10.0 kN/mm$^2$.*

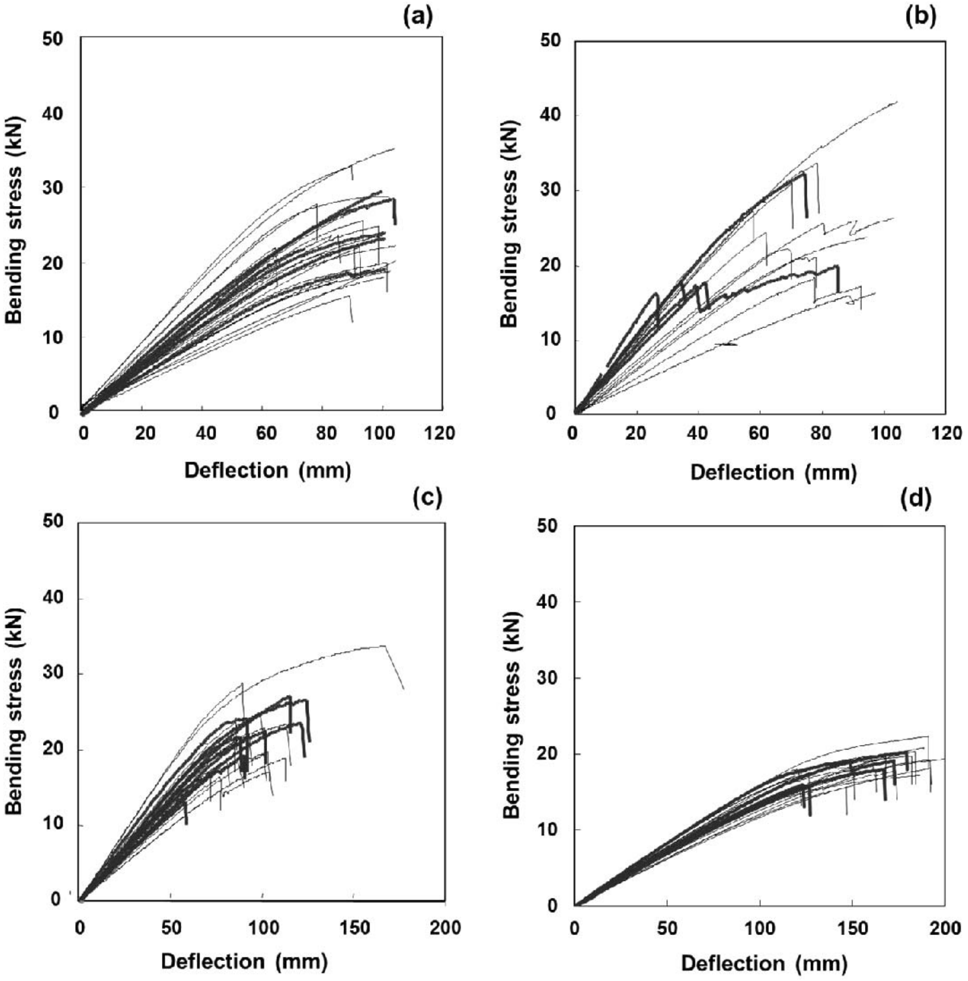

*Figure 9.—Relationship between load and deflection: (a) Japanese cedar lumber, (b) Japanese cypress lumber, (c) Japanese cedar glued laminated timber, and (d) Japanese cypress glued laminated timber. Load span of a, b, and c is 2,700 mm and of d is 3,600 mm. Thick lines in a and b represent lumber from damaged trees with CF and thick lines in c and d represent damaged glued laminated timber. Thin lines in a and b represent lumber from damaged tree without CF and thin lines in c and d represent normal glued laminated timber.*

without CF for Japanese cypress while it is not different for Japanese cedar regardless of whether CF was present. The analysis of the difference among the two species is given below. The MOE was calculated from the initial gradient of these curves, and the MOR was calculated from the maximum load values. Because the MC of each specimen was around 15 percent, there was no water content rate correction for either MOE or MOR. Table 3 summarizes MOE and MOR by tree species and the presence of CF. According to another study, lumber from normal trees from the same prefecture had an MOE of 7.8 ± 1.2 kN/mm$^2$ (mean ± SD) and an MOR of 45.8 ± 9.5 N/mm$^2$ for Japanese cedar and an MOE of 10.4 ± 1.3 kN/mm$^2$ and an MOR of 60.0±10.6 N/mm$^2$ for Japanese cypress (Aichi Prefectural Government Office and Aichi Prefecture Federation of Wood Association 2016). When we compare this normal tree data with those in Table 3, the bending properties of the lumber from damaged Japanese cedar trees were not inferior in terms of MOE or MOR regardless of whether CF was present. On the other hand, for Japanese cypress, while the MOE values were similar between the normal tree data and those of the lumber from damaged trees regardless of whether CF was present, the MOR values of the lumber from damaged trees were lower than those from normal trees, again regardless of whether CF was present.

Figure 10 shows the relationship between the MOE and MOR of lumber from damaged trees and also shows the design strength value for each species as given by the Japanese Building Standards Act (Ministry of Land, Infrastructure, and Transport 2007). This design strength value is the lower 5 percent limit for numerous experimental data gathered within Japan. For Japanese cedar, regardless of whether CF was present, as MOE increases, MOR also increases, and the two are linearly correlated ($r^2 = 0 .489$, $P < 0.01$, and $r^2 = 0.696$, $P < 0.05$, respectively) (Fig. 10a). Regardless of the presence of CF, the MOR of all lumber from damaged trees exceeded the standard strength. For Japanese cypress, the MOR of lumber from damaged trees without CF, as with the cedar, increased with increasing MOE, linearly correlated ($r^2 = 0.342$, $P < 0.05$) and exceeded the design strength value (Fig. 10b). However, for lumber from damaged cypress with CF, there was no significant correlation between the MOR and MOE ($r^2 =$

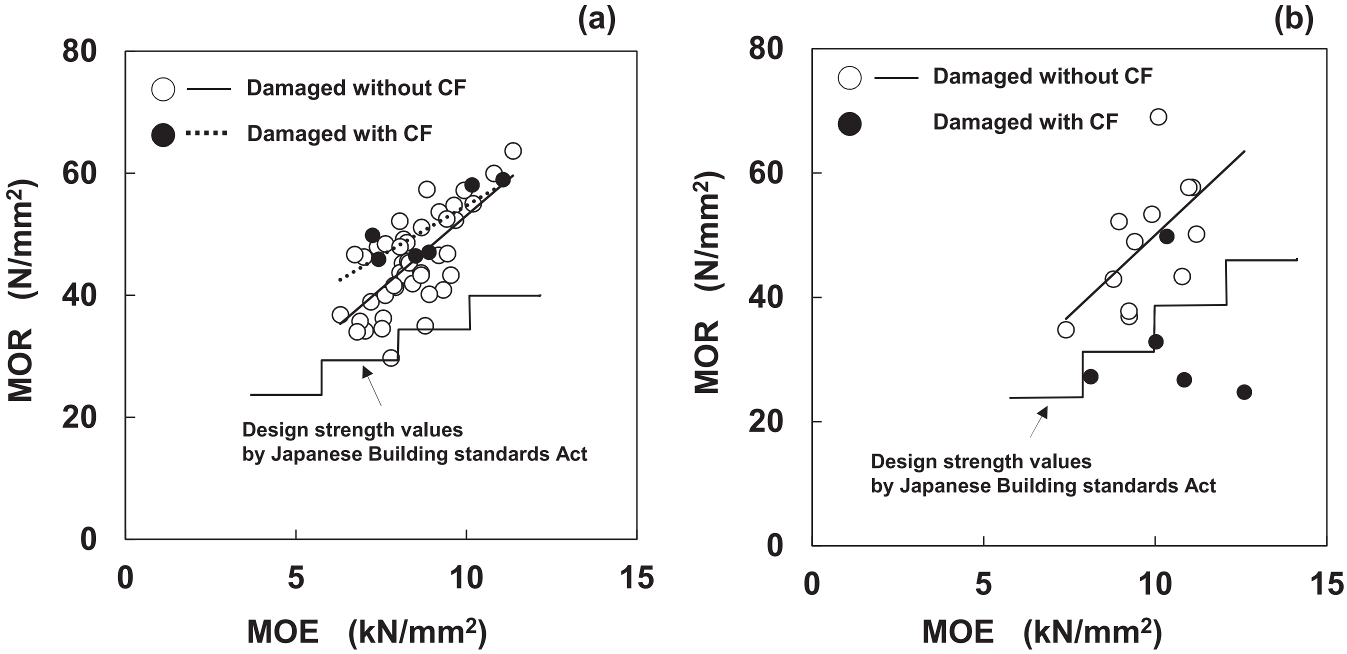

*Figure 10.—Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) of lumber from damaged trees: (a) Japanese cedar and (b) Japanese cypress. The stepped solid lines illustrate the design strength value set by the Ministry of Land, Infrastructure, and Transport (2007). CF = compression failure.*

0.018, $P = 0.83$), and even in lumber with a high MOE, the MOR fell below standard strength (all but one specimen were under 32 N/ mm$^2$). This is similar to the findings of Arnold and Steiger (2006), who used full-scale Sitka spruce lumber to investigate the effects of CF on MOE and MOR. They found that while the effects of CF on MOE were miniscule, CF had a clear negative effect on MOR, which was significantly lower in lumber with CF than in lumber without. Although our results for the Japanese cypress were similar to those for the Sitka spruce, they were different for the Japanese cedar, in which both MOE and MOR remained unaffected by CF. This indicates that the effects of CF on MOR are specific to each tree species.

Figure 11a gives the deflection energy calculated by the area under deflection versus load curve before maximum load obtained in the bending test for lumber from damaged trees. According to these results, CF has little effect on the deflection energy of Japanese cedar, but it does affect that of Japanese cypress. That is, the average value of Japanese cypress without CF was 1,174 kN/mm, while that of Japanese cypress with CF was 763 kN/mm, 38 percent lower. But there was no significant difference ($P = 0.07$). Thus, we can conclude that the bending behavior of the Japanese cypress specimens tended to be brash as a result of the CF. Figures 12a and 12b show examples of bending failure of lumber from Japanese cedar and Japanese cypress, respectively. In most cases with Japanese cedar, there was pulling of fibers on the tension side, which was robust and resistant to failure behavior; this is generally similar to failure in normal Japanese cedar. However, in the Japanese cypress, in most specimens, cracks appeared in the parts of the lumber with CF, and these cracks quickly progressed to the neutral axis area, causing failure. This supports the notion that Japanese cypress is made brash by CF.

## Full-scale bending properties of damaged glued laminated timber

Figures 9c and 9d show the load-deflection curves for glued laminated timber from damaged trees (thick lines) and normal trees (thin lines) of Japanese cedar and of Japanese cypress, respectively. The MOE and MOR of each were calculated as described above for the lumber, also without any water content rate correction. Figure 13 shows the relationship between MOE and MOR for the glued laminated timber from normal and damaged trees. The MOR for both Japanese cedar (Fig. 13a) and Japanese cypress (Fig. 13b) increased with increasing MOE regardless of whether the trees had been damaged. However, if we look at the regression lines, it is seen that the trends differed between the two species. For Japanese cedar, the regression lines for normal and damaged glued laminated timbers almost overlap. However, for Japanese cypress, the line for damaged glued laminated timber is lower than that for normal glued laminated timber. An analysis of covariance was therefore conducted to see whether the regression line for the normal timber is higher than for the damaged timber. For both species, the slope of the line was not significantly different from each other ($F = 1.5$ for Japanese cedar, $F = 1.9$ for Japanese cypress). In contrast, the intercept of the line was not significantly different for Japanese cedar ($F = 0.38$), although it was for Japanese cypress ($F = 5.7$, $P < 0.05$). Thus, for Japanese cypress glued laminated timber, even when composed from laminae without CF, the MOR of the damaged tree was significantly lower than that for the normal tree.

The deflection energy calculated by the area under deflection versus the load curve before the maximum load obtained in the full-scale bending test for the glued laminated timber is given in Figure 11b. Note that since the span of the bending test for the two species differs, we

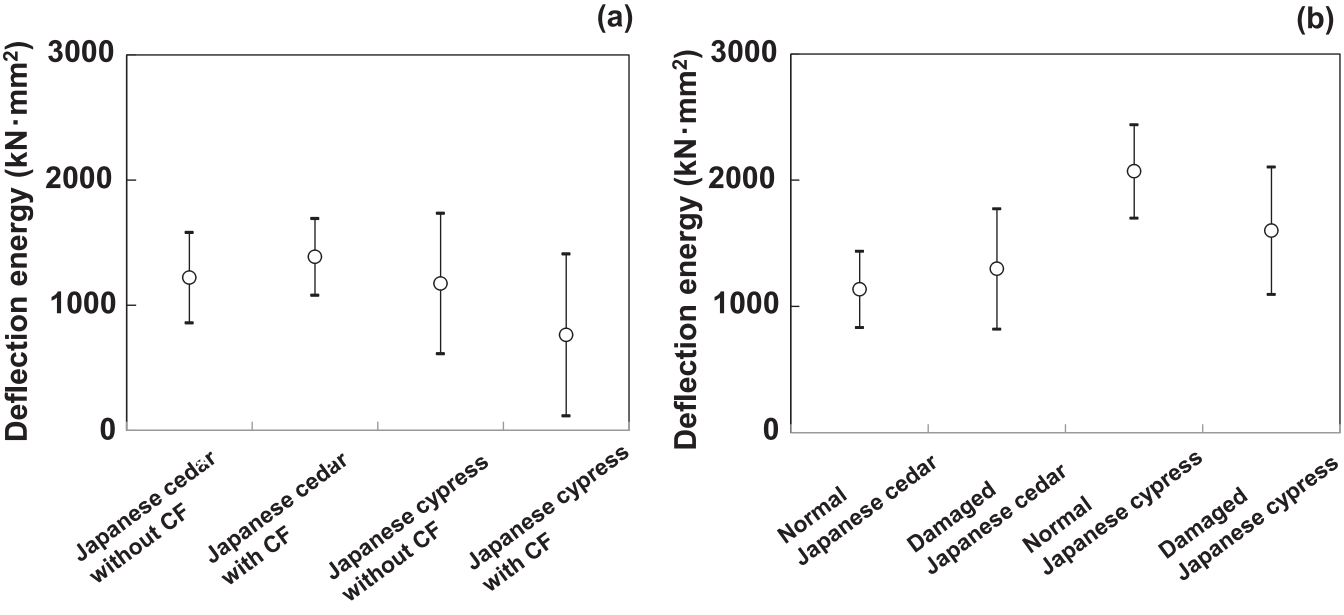

*Figure 11.—Deflection energy calculated by the area under deflection versus load curve before the maximum load for lumber and glued laminated timber: (a) lumber and (b) glued laminated timber. Circles show the average of deflection at maximum load. Error bars show standard deviations. CF = compression failure.*

cannot compare them directly. For the Japanese cedar, the deflection energy was not significantly different from each other for normal and damaged ($P = 0.32$); in other words, there was no effect of damage on deflection energy. However, for Japanese cypress, the average of deflection energy of normal glued laminated timber was 2,071 kN/mm (load span, 3,600 mm), while that of damaged was 1,602 kN/mm (load span, 3,600 mm), 23 percent lower ($P < 0.05$).

Matsumura et al. (1993) showed that even if no CF are visible to the naked eye in lumber taken from logs with CF, there may be minute compression failure (MCF) in the lumber. Furthermore, they indicated the potential for MCF to cause small reductions in strength. Kitahara et al. (1984) also used small samples of Japanese cedar and found that specimens that were repeatedly subjected (15 times) to a static load of 30 percent of their MOR, within their elasticity range, suffered from microscopic wrinkles in their cell walls and a reduction in their bending energy before they reached maximum deflection. These results suggest that MCF may have been present in the damaged glued laminated timber tested in the current study. If there was MCF in both species, then it is possible that MCF has no effect on MOR in Japanese cedar but does have an effect in Japanese cypress, resulting in reduced strength.

As stated above, the bending tests showed that the MOR was more strongly affected by CF in Japanese cypress than in Japanese cedar. In general, Japanese cypress has superior strength properties to Japanese cedar. However, when the MOE is similar, Japanese cedar has a larger MOR. In

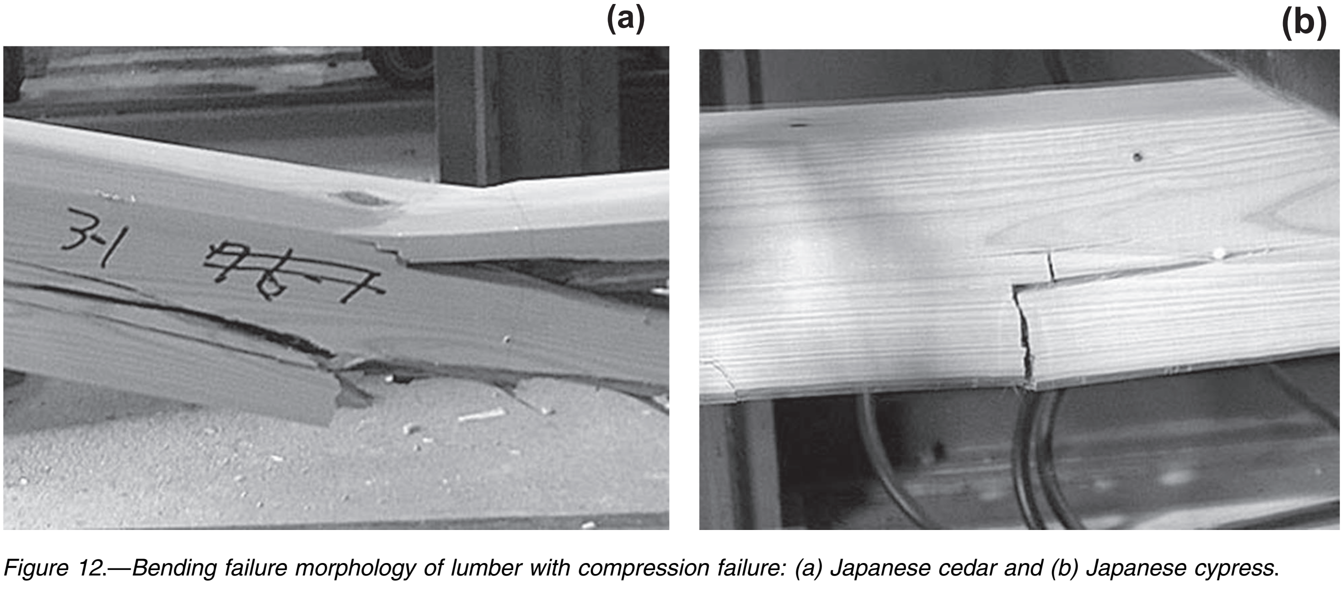

*Figure 12.—Bending failure morphology of lumber with compression failure: (a) Japanese cedar and (b) Japanese cypress.*

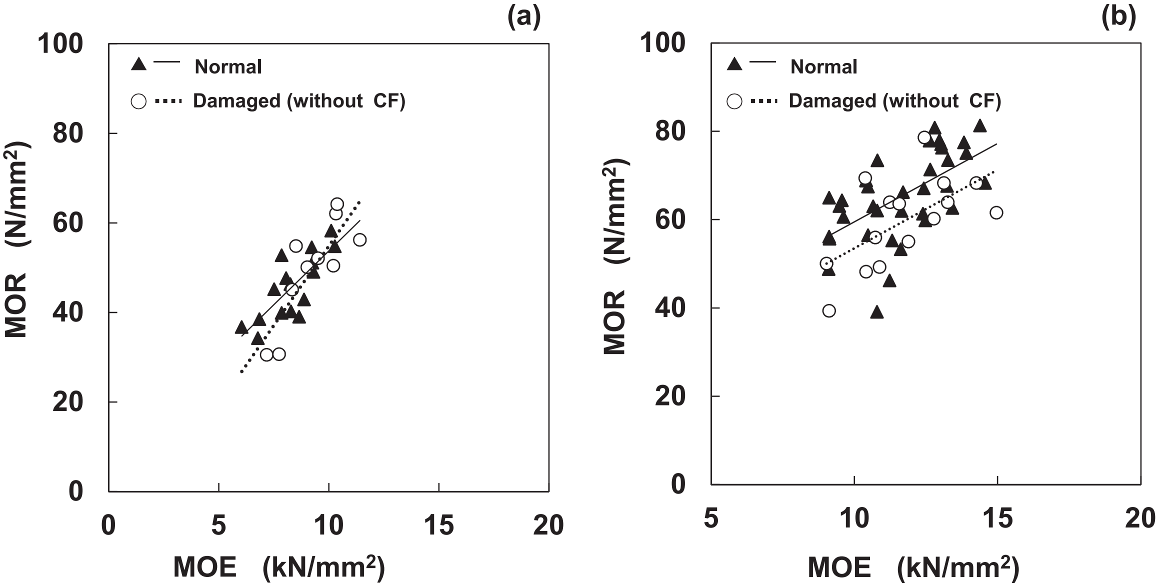

*Figure 13.—Relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) of normal and damaged glued laminated timber: (a) Japanese cedar and (b) Japanese cypress. CF = compression failure.*

bending tests of Japanese cedar, failure on the tension side does not lead to overall failure, and Japanese cedar is able to withstand loads with a very large deflection. That is, Japanese cedar is considered to have a greater toughness and deformability. The tests in the current study also investigated the ratio of MOR to MOE (MOR/MOE; Table 6). The MOR/MOE of lumber from damaged trees was higher for Japanese cedar than for Japanese cypress regardless of the presence of CF. In addition, Japanese cypress lumber with CF had a lower MOR/MOE than that without. In the case of glued laminated timber, there was no difference in MOR/MOE between the two species for normal trees, but for glued laminated timber from damaged trees, the MOR/MOE was lower for Japanese cypress. This indicates that Japanese cedar has greater toughness than Japanese cypress, which is not affected by damage, but that damage does affect Japanese cypress and reduces its deformability.

## Conclusions

This study investigated the usability, as structural lumber, of two of Japan's staple production species—Japanese cedar and Japanese cypress—when they have been damaged by wind. Specifically, it first surveyed the state of damage of affected forests and the occurrence of CF for each damage type. It then investigated the relationship between the dynamic Young's modulus of the lumber and the rate of occurrence of CF. Finally, it investigated the strength properties of lumber and glued laminated timber from damaged trees.

1. Approximately 70 percent of the damaged forests surveyed had a high stand density and high DBH-H ratios. Overturned trees made up about 60 percent of all trees in these forests.
2. The rate of occurrence of CF for each damage type was highest for logs that had undergone bending. For the lumber, wood taken from inclined and bending trees had the highest rate of CF. Furthermore, for overturned trees, even when CF was not observed in the logs, it was sometimes observed in the lumber. The relationship between the dynamic Young's modulus and the rate of occurrence of CF in lumber was slightly positive for both Japanese cedar and Japanese cypress.
3. With respect to the bending properties of lumber from damaged trees with CF, for Japanese cedar an increase in MOE was followed by an increase in MOR regardless of whether CF was present, and all of the test specimens exceeded the standard strength. In contrast, for Japanese cypress, while lumber from damaged trees without CF showed a similar trend to that for Japanese cedar, that with CF showed no correlation between MOE and MOR, and most specimens fell below the standard strength.
4. With respect to the bending properties of damaged glued laminated timber that used CF-free laminae and those of normal glued laminated timber, the MOR increased with

*Table 6.—Ratio of modulus of rupture (MOR) and modulus of elasticity (MOE) for lumber and glued laminated (GL) timber.*

| | | Japanese cedar | | Japanese cypress | |
|---|---|---|---|---|---|
| Specimen type | Condition[a] | *n* | MOR/MOE, mean (SD) | *n* | MOR/MOE, mean (SD) |
| Lumber | Without CF | 43 | 5.3 (1.0 ) | 12 | 4.9 (0.8) |
| | With CF | 6 | 5.8 (0.6) | 5 | 3.2 (1.1) |
| GL timber | Normal | 16 | 5.5 (0.3) | 40 | 5.4 (0.8) |
| | Damaged | 10 | 5.4 (0.6) | 16 | 4.7 (0.9) |

[a] CF = compression failure.

increases in MOE for both. However, the Japanese cedar showed no significant difference between both normal and damaged glued laminated timber, while for Japanese cypress the MOR of the normal glued laminated timber was significantly greater than that of the damaged glued laminated timber.

These results indicate that the effects of CF on the strength properties of wood are species specific and differ between Japanese cedar and Japanese cypress. In the case of Japanese cedar, the results show that there is no need for special consideration when using this species as structural lumber if MCF is present. However, in the case of Japanese cypress, even when CF was not visible to the naked eye, some cases were found in which the strength of the wood had declined. The use of damaged Japanese cypress as structural lumber therefore requires some special consideration of this issue.

## Literature Cited

Aichi Prefectural Government Office and Aichi Prefecture Federation of Wood Association. 2016. The guidance of utilization of wood produced in Aichi prefecture. Aichi Prefecture Federation of Wood Association, Nagoya, Japan. pp. 8–9. (In Japanese.)

Arnold, M. 2003. Compression failures in wind-damaged spruce trees. *In*: Proceedings of the International Conference Wind Effects on Tree, September 16–18, 2003, University of Karlsruhe, Germany; University of Karlsruhe. pp. 253–260.

Arnold, M. and R. Steiger. 2006. The influence of wind-induced compression failures on the mechanical properties of spruce structural timber. *Mater. Struct*. 40:57–68.

Faust, T. D., M. M. Fuller, R. H. McAlister, and S. J. Zarnoch. 1994. Assessing internal hurricane damage to standing pine poletimber. *Wood Fiber Sci*. 26(4):536–545.

Fujimori, T. 1995. Relationship between stand ages and wind resistance of stand–forest damage by Typhoon 7 in 1959 in the Tokyo Regional Forestry Office, Japan. *J. Jpn. Forest Soc*. 77(6):602–605.

Fujimoto, N., H. Hisatomi, Y. Fujimoto, J. Kawabe, and Y. Mataki. 1995. Relationship cell wall deformation and mechanical properties of sugi and hinoki woods damaged by typhoon. *Bull. Kyushu Univ. Forests* 73:35–42. (In Japanese with English summary.)

Gresham, C. A., T. M. Williams, and D. J. Lipscomb. 1991 Hurricane Hugo wind damage to southeastern U.S. coastal forest tree species. *Biotropica* 23(4):420–426.

Isamoto, N. and T. Takamiya. 1992. Factor analysis of forest damages in Oita prefecture by Typhoon 19th (1991. 9). *Jpn. J. Forest Environ*. 34(2):98–105. (In Japanese.)

Kitahara, R., J. Tsutsumi, and T. Matsumoto. 1984. Effect of static bending-load on the mechanical behaviour of wood. *Mokuzai Gakkaishi* 30(7):522–529. (In Japanese with English summary.)

Kokura, M., Y. Mori, and S. Mibayashi. 1993. Properties of wood damaged by No. 19 typhoon in 1991. *Bull. Ishikawa Pref. Forest Exp. Sta*. 24:31–36. (In Japanese.)

Kord, B. 2007. Effects of compression failure on the mechanical properties of *Pinus* wood in an experimental planting in north of Iran. *In:* Proceedings of the 16th International Symposium of the IIWC, November 11–16, 2007, Florence, Italy; International Council on Monument on Site.

Matsumura, J., K. Oda, S. Takata, and J. Tsutsumi. 1993. Relationship cell wall deformation and mechanical properties of sugi and hinoki woods damaged by typhoon. *Sci. Bull. Fac. Agric. Kyushu Univ*. 48:27–33. (In Japanese with English summary.)

Midori, M., H. Shiroi, and Y. Ashihara. 1992. Wood properties of Japanese cedar damaged by typhoon. *Annu. Rep. Oita Pref. Forestry Exp. Sta*. 34:52–59. (In Japanese.)

Ministry of Land, Infrastructure, and Transport. 2007. Japanese Building Standards Act. http://www.jlira.jp/data/jas_file11.pdf. (In Japanese.)

Miyajima, H. 1959. Compression failures in wood from trees damaged by typhoon 15 of 1954. *Bull. Forestry Hokkaido Univ*. 20(1):197–208. (In Japanese with English summary.)

Nagoya Meteorological Observatory. 2009. Aichi prefecture weather bulletins about the typhoon no. 18 in October 2009. Nagoya Local Meteorological Observatory, Nagoya, Japan. (In Japanese.)

Ogaya, S. 2002. The Manual for Artificial Forests Thinning. National Forestry Promotion Association, Tokyo. pp. 14–18. (In Japanese.)

Reilly, A, E. 1991. The effect of hurricane Hugo in three tropical forests in the U.S. Virgin Islands. *Biotropica* 23(4a):414–419.

Ruel, J. C., A. Achim, R. E. Herrera, A. Cloutier, and B. Brossier. 2010. Wood degradation after windthrow in northern environment. *Forest Prod. J*. 60(2):200–206.

Tsuboki, K., M. K. Yoshioka, T. Shinoda, M. Kato, S. Kanada, and A. Kitoh. 2015. Future increase of supertyphoon intensity associated with climate change. *Geophys. Res. Lett*. 42(2):646–652.