Analytical Approach to Determining the Effects of Incising on Bending Strength and Stiffness of Glued Laminated Beams[1]

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Abstract: No engineering design adjustment factor for incising and waterborne-preservative treatment effects is currently required for glued laminated construction. This lack of understanding of the incising effect is a critical issue that deserves additional consideration before any modifications to American Wood Preservers' Association (AWPA) Standard C-28 (AWPA 1997) are adopted. A recent study has shown that dry lumber, especially when incised to depths exceeding 10 mm (0.4 in.), can be extremely sensitive to incising-related strength losses, which can exceed 50%. Accordingly, this issue is of concern because glued laminated timber beams are incised dry and incising IS required to a 12.5-mm (0.5-in.) depth. In this study, our analysis and discussion show that, for glued laminated timber beams ranging from 6 to 20 laminations, potential strength and stiffness can be reduced from 19% to 6% and 10% to 3%, respectively, depending on beam size and incising depth.

INTRODUCTION

Incising reduces the strength and stiffness of actual 38-mm (nominal 2-in.) incised and treated lumber (Perrin 1978, Lam and Morris 1991, Winandy et al. 1995). Losses due to incising can also occur in solid timbers of larger size (Harkom and Rochester 1930, Rawson 1927) and in glued laminated members (Schrader 1945).

A recent study (Winandy and Morrell 1998) evaluated the effects of pretreatment incising of dry lumber and subsequent waterborne-preservative treatment on the bending strength of 1,980 pieces of actual 38- by 89-mm by 3.6-m-long (nominal 2- by 4-in. by 12-ft. long) dimension lumber. In that study, three species groups (Douglas Fir, Hem-Fir. and Spruce-Pine-Fir South) and two commercially produced machine-stress-rated grades per species group were evaluated. Two incision densities (7,000 and 8,500 incisions/m^2), four incision depths (0, 5, 7, and 10 mm (0, 0.2, 0.3, and 0.4in.)),and three preservative types (CCA, ACZA, and ACQ-B) were evaluated. The tested effects on bending strength of 38-mm- (2-in.-) thick dry lumber were found to be between a 20% and 30% reduction when incised up to 7 mm (0.3 in.) deep. However, in some cases, the observed strength loss exceeded 50% when dry lumber was deeply incised in excess of 10 mm (0.4 in.) deep.

Recent changes to the National Design Specification for Wood (ANSI/AF&PA 1997) now require a 15% reduction in allowable design stresses in bending

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and a 5% reduction in stiffness for incised lumber used green or dry. The Canadian Design Code for Wood (CSA 1989) requires a 15% reduction in allowable design stresses in bending and a 5% reduction in stiffness for incised lumber when used wet. When incised lumber is used in a dry condition, the Canadian code requires a 30% reduction in allowable bending stresses and a 10% reduction in stiffness.

METHODS

In this study, the reduced section-modulus method first proposed by Luxford and Zimmerman (1923) is re-evaluated. Their unproven theory states that the effect of the incising process is directly related to the change in section modulus induced by incising. After we developed a model based on reduced moment of inertia for incised beams, which was clearly based on their theory, we then directly compared predictions from our model to their actual data from incised 100-mm- (4-in.-) wide by 200-mm- (8-in.-) deep by 2.4-m- (8-ft-) long timber. After showing reasonable agreement between our predictions and their data on timbers. we then independently verified our model by comparing predictions from the model to an independent set of data from 1,980 pieces for three species of incised actual 38- by 89-mm (nominal 2- by 4-in.) lumber (Winandy and Morrell 1998). Finally, after these comparisons indicated that our models could accurately predict losses in *strength* and stiffness from incising, the models were used as a basis for evaluating the effects of incising on the strength and stiffness of various sizes of glued laminated timber.

MODEL DEVELOPMENT

Analytical Prediction of Incised Timbers

Luxford and Zimmerman (1923) tested two matched groups of incised specimens and an nonincised control; one group was perforated green, air-dried. and left untreated and another group was perforated green. air-dried. and then treated. The modulus of rupture and modulus of elasticity results for these groups are summarized in Table 1. Luxford and Zimmerman (1923) state that the observed reduction in strength of their incised specimens to that of their control group was approximately equal to the reduction in section modulus. They made no statement with respect to modulus of elasticity. Their specimens were 100 mm (4 in.) wide by 200 mm (8 in.) deep by 2.4 m (8 ft) long and were tested in a third-point bending setup across a support span of 2.25 m (90 in). The incisions were approximately 3.1 mm (0.125 in.) wide by 19 mm (0.75 in.) long, and 19 mm (0.75 in.) deep and had a staggered pattern such that the cross sections repeated every 51 mm (2 in.) along the longitudinal axis of the member. The incisions were spaced 6 mm (0.25 in.) apart across the width of the members. At a given cross section, the gross moment of inertia would be 7.1 x 10^6 mm^4 (170.6 in^4) and the reduced moment Of inertia would be 6.4 x 10^6 mm^4 (153.5 in^4). This results in a reduced moment of inertia that is 90% of the gross moment of inertia. The calculations are shown in the Appendix.

The two groups of perforated timbers had a loss in modulus of rupture of 0.86 and 0.85, respectively, compared with the control group. These ratios of strength loss due to incising closely match (within 5%) the ratio of reduced moment of inertia (0.90). For modulus of elasticity, the two groups of perforated timbers had a ratio of 0.95 and 0.97 with the control group results.

Based on this comparison, it is apparent that reduced moment of inertia is not a good predictor of stiffness loss. A possible explanation for these observed differences is that strength is a local property and stiffness is a global property. The reduced moment of inertia calculation assumes that the entire length of the beam has a reduced cross section. This assumption is probably appropriate for bending strength, because the section with the greatest strength-reducing defect normally governs the strength of the entire member. However, that same assumption might not apply to stiffness because a single reduced cross section does not generally determine the stiffness of the overall member. Rather, overall member stiffness usually reflects the contribution of all cross sections along the length of the member.

To address this, the 2.25-m- (90-in.-) long member with the third-point loading was re-analyzed with alternating reduced and full cross sections at every 25-mm (l-in.) increment along the member. This corresponds to the 50-mm (2-in.) incision spacing reported by Luxford and Zimmerman (1923). This alternating cross section analysis is most appropriately handled using a complementary virtual work method (Hernandez et al. 1992). This method predicts the total deflection of a bending member given incremental cross section information along the whole length of the beam. The stiffness reduction due to this incision pattern was calculated to be 0.95, which compares well with the actual values of 0.95 and 0.97. Thus, Luxford and Zimmerman (1923) found that the reduction in moment of inertia was a good predictor of reduction in bending strength. However, in this study, we found that the reduction in bending stiffness was best predicted when the alternating solid and reduced (incised) cross sections along the whole length of the beam were considered in the calculations.

Applying the Models to incised Lumber

Before we could model the data from the study of Winandy and Morrell (1998), we had to characterize the actual dimensions and geometry of the two extremes in the incision patterns and types studied. The most visually apparent difference between the knife-like j-mm-deep incision and the chisel-tooth 7-mm-deep incision is the size of the opening that remains on the surface of the lumber. Figures 1 and 2 compare the 5- and 7-mm-deep incision openings. The 5-mm-deep incision opening has characteristics that would be expected from a sharp knife-type puncture on the wood surface. The ends of the incision come to a sharp point, indicating the wood fibers were separated (rather than sheared) during incising. The 7-mm-deep incision, on the other hand. shows a much wider surface opening. The ends of the incision show evidence that wood fiber was cut or sheared, thereby inducing more wood damage during this type of incising. This characteristic was referred to as crow's feet by Winandy and Morrell (1998).

We also measured the incision depths of groups of treated and incised lumber that had various densities and depths of incisions. The measurements were made on lumber cross sections cut at the center of an incision at its deepest penetration. The results of these measurements are listed in Table 2.

Based on the results in Table 2, it appears that the following statements can be made:

1. For groups that had 7,000 incisions/m', the actual depths of the incisions were approximately equal to the targeted nominal depth.

2. For groups that had 8,500 incisions/m^2, the actual depths of the incisions were approximately 65% of the targeted nominal depth. This indicates that higher pressures would have been necessary to transfer the same amount of load per incision as the 7,000/m^2 group.

3. For similar species and treatments, the depth of incision was slightly larger for the lower grade of MSR lumber (in most cases). This would be expected because the lower grade of MSR lumber corresponds to lower specific gravity, and penetration would be more easily achieved.

Damaged Area

An additional characterization was the amount of wood damage caused by the incising. A few specimens were cut along the transverse and longitudinal axes of the incisions to allow us to observe the incision profile. Figure 3 through 6 show the incision profiles for both the knife-like 5-mm-deep and chisel-type 7-mm-deep incisions, respectively. These photos correspond to the same specimens used in the top-view photos in Figures 1 and 2. The end-views (Figs. 3 and 4) clearly show a marked difference in the width and the wood-damage area beneath the knife-like 5-mm-deep incision with a density of 8,500 incisions/m' (Fig. 3) and the chisel-tooth 7-mm-deep incision with a density of 7,000 incisions/m^2 (Fig. 4).

Figures 5 and 6 show that the amount of wood that is damaged beneath the incision depth covers a much larger area than the actual incision depths that were reported in Table 2. For example, Figure 5 represents a knife-like 5-mm-deep incision (density of 8,500 incisions/m') in a piece of CCA-treated 2,400 f/2.0E Hem-Fir lumber. Based on the pin-hole reference points that were 6.4 mm (0.25 in.) apart, the measured incision depth would have been approximately 2.9 mm (0.11 in.). This would correspond to the measurements taken on specimens like those shown in

Figures 3 and 4. When the damaged area is included, the incision depth is approximately 4.5 mm deep. Thus, the depth of the damaged area caused by incising could be approximately 1.6 times the measured incision depth. For the chisel-tooth 7-mm-deep incision shown in Figures 4 and 6, the ratio for the depth of the damaged area beneath the incision to the actual incision depth was approximately 1.5.

Analysis of Incised Lumber

For the actual 38-mm- (nominal 2-in-) thick lumber data reported by Winandy and Morrell (1998), the same calculation methods as described above and in the Appendix were applied. At a particular cross section, the spacing between incisions measured 12.5 mm (0.50 in.) for specimens that had 7,000 incisions/m^2 and 10 mm (0.40 in.) for specimens that had 8,500 incisions/m^2. For the 7,000-incisions/m^2 specimens, the nominal 5-mm-deep incisions were estimated to have an actual incision depth of 8 mm (0.32 in.) and a width of 1.5 mm (0.06 in.). The 7-mm-deep incisions were estimated to have an actual incision depth of 11 mm (0.43 in.) and a width of 2.5 mm (0.10 in.). For the 8,500-incisions/m^2 specimens, the nominal 5-mm-deep incisions were estimated to have an actual incision depth of 5.3 mm (0.21 in.) and a width of 1.5 mm (0.06 in.). The 7-mm-deep incisions were estimated to have an actual incision depth of 6.3 mm (0.25 in.) and a width of 2.5 mm (0.10 in.). These estimates are based on the actual depths reported in Table 2 and estimates of damaged areas beneath incisions as estimated from an analysis of photos similar to those shown in Figures 5 and 6.

Based on the estimated dimensions of the incisions (including an estimate of the damaged area directly beneath the incision) and using the maximum estimated reduced moment of inertia for modulus of rupture (MOR), the four groups were as follows:

7,000 incisions/m^2, 5-mm depth = **0.90** times gross moment of inertia
7,000 incisions/m^2, 7-mm depth = **0.79** times gross moment of inertia
8,500 incisions/m^2, 5-mm depth = **0.92** times gross moment of inertia
8,500 incisions/m^2. 7-mm depth = **0.86** times gross moment of inertia

Similarly, based on these estimated dimensions of the incisions (and damaged area beneath) and using the complementary virtual work method to globally estimate the reduced bending stiffness, the four groups were as follows:

7,000 incisions/m^2, 5-mm depth = **0.95** times gross moment of inertia
7,000 incisions/m^2, 7-mm depth = **0.88** times gross moment of inertia
8,500 incisions/m^2, 5-mm depth = **0.96** times gross moment of inertia.
8,500 incisions/m^2, 7-mm depth = **0.92** times gross moment of inertia

To compare with actual test results, the MOR and modulus of elasticity (MOE) results from Winandy and Morrell (1998) were normalized to each groups' respective control group. Comparisons were only made at the *mean* values. Table 3 shows these results.

Verification of Model for Incised Lumber and Timber

Based on the results in Table 3 and on results by Luxford and Zimmerman (1923) (Table 1), it appears that reduced moment of inertia could be a feasible predictor of reduced MOR due to incising. In addition, actual test data showed that the reduction in bending stiffness was less than the observed reduction in MOR. Thus, the assumption that the moment of inertia is reduced throughout the entire length of the member over-predicts the loss in bending stiffness. In this analysis, it was shown that the complementary virtual work method could be used to accurately predict the deflection of an incised beam, by considering the alternating full and reduced cross sections along the length of the member.

APPLICATION TO INCISED GLUED LAMINATED TIMBERS

Given the assumption that (i) the reduction in MOR could be predicted by the reduction in moment of inertia, and (ii) the reduction in bending stiffness could be predicted using a complementary virtual work method, 32 hypothetical glued laminated beam combinations were analyzed. The 24F-V4 Douglas Fir glued laminated beam combination, shown in Figure 7, was arbitrarily chosen. Four standard widths (79.3, 130.2, 171.5, and 222.3 mm (3.125, 5.125, 6.75, and 8.75 in.)) and eight depths (6-Lam to 20-Lam) were analyzed. For each analysis, a 21:1 span-to-depth ratio was assumed and a symmetric two-point loading was applied in the center 20% of the beam span. The nominal incision size was 3.8 mm (0.15 in.) wide by 12.5 mm (0.5 in.) deep. With the 1.5× factor used to account for the damaged area found beneath incisions in dry wood and discussed previously (Figs. 5 and 6), the total assumed incision depth was 18.8 mm (0.74 in.). The incisions were assumed to be spaced 19 mm (0.75 in.) across the width of the members, and the incised cross sections were spaced every 25.4 mm (1.0 in.) along the length of the member. Thus, the solid and reduced cross sections were spaced every 12.5 mm(0.5 in.). This assumed spacing corresponds to approximately 2,000 incisions/m^2.

The results of this hypothetical analysis of reduced strength and stiffness for the range of glued laminated beam lay-ups are given in Table 4. Based on the reduced moment of inertia assumption, the predicted reduction in MOR ranged from 0.812 for a 6-Lam. 79.3-mm- (3.125-in.-) wide beam to 0.935 for a 20-Lam, 222.3-mm- (8.75-in.-) wide beam (Fig. 8). For bending stiffness, the reductions ranged from 0.896 for a 6-Lam, 79.3-mm- (3.125-in.-) wide beam to 0.967 for a 20-Lam, 222.3-mm- (8.75-in.-) wide beam (Fig. 9).

Thus, for a 24F-V4 glued laminated beam combination, reductions due to incising were approximately 7% to 19% for bending strength and approximately 3% to 10% for bending stiffness. The calculated reductions will be influenced by changes in number of laminations. beam width, and grades of laminations.

CONCLUSIONS

Our analysis showed that a model based on the reduced moment of inertia approach reasonably predicted loss in bending strength. Further, a model based on a complementary virtual work method was reasonably able to predict reductions in bending stiffness. Using these approaches, we then showed that incising can extensively reduce the strength and stiffness of glued laminated beams. This incising effect is a function of beam size and properties, incising depth, incising density, and tooth design. Current AWPA standards do not define the maximum or minimum parameters as to depth, density, or permitted tooth design. Nor do they account for the moisture content of wood at the time of incising, which can have a considerable influence on wood damage beneath and around the incisions and its effects on wood strength.

Current engineering standards do not require adjustments to strength or stiffness for incised and treated glued laminated timber beams. Previous research has shown that dry actual 38- by 89-mm (nominal 2- by 4-in.) lumber is especially sensitive to deep incising, sometimes experiencing strength losses of up to 50%. Accordingly, because glued laminated timber is incised dry, these strength losses in the critical tension laminations must be further studied before revisions are made in AWPA standards that will permit deep incising and waterborne-preservative treatment of glued laminated timber beams. The AWPA, glue laminators, and their agencies need to work together to account for their potential losses in strength and stiffness when glued laminated timber is incised and treated with waterborne-preservatives.

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APPENDIX

This appendix shows calculations of gross and reduced moment of inertia (I) for Luxford and Zimmerman (1923) specimens.

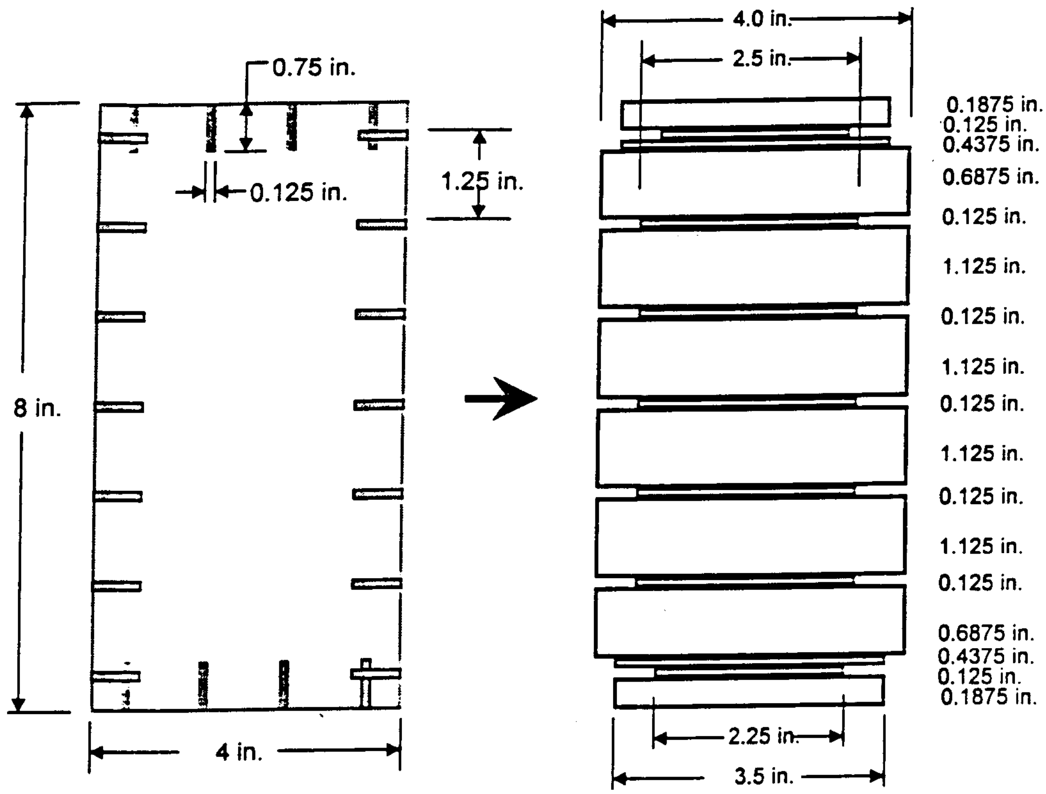

Figure A- 1. Hypothetical example of converting actual timber size and incising pattern (left) as reported by Luxford and Zimmerman (1923) to a revised section (right) for the reduced moment of inertia model.

Gross Moment of Inertia

$I_{gross} = bh^3/12 = (4 \text{ in.})(8 \text{ in.})^3/12$ **$I_{gross} = 7.1 \times 10^6$ mm^4 (170.6 in^4)**

where b is base and h is height. Reduced moment of inertia was determined by "collapsing" the width based on the incision widths and depths. This results in a cross section with 17 layers. Parallel axis theorem was then used to determine the reduced moment of inertia.

Reduced Moment of Inertia

$I_{reduced} = 6.4 \times 10^6$ mm^4 (153.5 in^4)

Table l—Average values of modulus of rupture (MOR) and modulus of elasticity (MOE) from the results of Luxford and Zimmerman (1923)

Group	Sample size	MOR (MPa	(lb/in^2))	MOE (GPa	(lb/in^2 ′ 10^6))
Perforated green and air-dried	10	60.81	(8,820)	13.68	(1.984)
Perforated green air-dried, and treated	10	60.46	(8,770)	14.00	(2.031)
Control group	30	70.92	(10,287)	14.42	(2.091)

Table 2—Actual incision measured depths and coefficient of variation (%, in parentheses) from lumber cross sections of Winandy and Morrell (1998)

				Actual incision depth (mm)			
				7,000 incisions/m^2		8,500 incisions/m^2	
Species group[a]	Grade	Treatment	Specific gravity	5-mm target depth	7-mm target depth	5-mm target depth	7-mm target depth
HF	16.5Of/1.5E	CCA	0.43	5.0 (29.5)	7.5 (19.1)	3.6 (3 1.5)	—
	2400f/2.0E	CCA	0.48	4.8 (23.8)	6.6 (25.0)	3.2 (35.2)	—
HF	1650f/1.5E	ACZA	0.44	5.3 (23.7)	8.7 (17.8)	3.5 (25.6)	4.7 (17.0)
	2400f/2.0E	ACZA	0.48	5.2 (21.7)	8.3 (18.8)	3.2 (21.7)	4.0 (23.5)
DF	1800f/1.8E	ACZA	0.46	5.0 (27.6)	7.9 (27.5)	3.3 (23.7)	3.9 (23.2)
	2400f/2.2E	ACZA	0.52	5.0 (26.5)	6.9 (33.8)	2.8 (36.6)	4.3 (62.1)
SPF-S	1650f/1.5E	CCA	0.43	—	7.2 (32.6)	3.7 (28.3)	—
	2250f/1.9E	CCA	0.47	—	7.2 (27.1)	3.0 (27.8)	—
SPF-S	1650f/l.5E	ACQB	0.43	—	8.0 (26.6)	3.0 (30.4)	—
	2250f/1.9E	ACQB	0.47	—	8.7 (106.3)	3.3 (26.2)	—

[a]HF. Hem-Fir: DF, Douglas Fir; SPF-S Spruce-Pine-Fir South.

Table 3—Normalized modulus of rupture (MOR) and modulus of elasticity (MOE) for incised 1umber[a]

				Normalized MOR (and MOE)			
				7,000 incisions/m^2		8,500 incisions/m^2	
Species group[b]	Grade	Treatment	Specific gravity	5-mm target depth	7-mm target depth	5-mm target depth	7-mm target depth
HF	1650f/1.5E	CCA	0.43	0.90 (0.91)	0.69 (0.88)	0.87 (0.92)	0.86 (0.94)
	2400f/2.0E	CCA	0.48	0.84 (0.90)	0.65 (0.79)	0.92 (0.92)	0.87 (0.91)
HF	1650f/1.5E	ACZA	0.44	0.89 (1.03)	0.68 (0.91)	0.89 (1 .00)	0.92 (1.02)
	2400f/2.0E	ACZA	0.48	0.89 (0.96)	0.68 (0.93)	0.90 (0.99)	0.83 (1.01)
DF	1800f/1.8E	ACZA	0.46	0.79 (0.87)	0.55 (0.74)	0.82 (0.92)	0.77 (0.84)
	2400f/2.2E	ACZA	0.52	0.86 (0.88)	0.62 (0.78)	0.84 (0.97)	0.78 (0.86)
SPF-S	1650f/1.5E	CCA	0.43	—	0.82 (0.96)	0.87 (0.95)	—
	2250f/1.9E	CCA	0.47	—	0.74 (0.91)	0.90 (0.92)	—
SPF-S	1650f/1.5E	ACQB	0.43	—	0.68 (0.81)	0.82 (0.98)	—
	2250f/1.9E	ACQB	0.47	—	0.69 (0.82)	0.77 (0.87)	—
Average of normalized data				0.86 (0.93)	0.75 (0.85)	0.86 (0.94)	0.84 (0.93)
Predicted from reduced moment of inertia				0.90 (0.95)	0.79 (0.88)	0.92 (0.96)	0.86 (0.92)

[a]Normalized values were obtained by dividing averages of the incised group by averages for the control groups. First numbers are normalized MOR and numbers in parentheses are normalized MOE,

[b]HF, Hem-Fir; DF, Douglas Fir; SPF-S Spruce-Pine-Fir South.

Table 4—Hypothetical reductions in bending strength as predicted by 1 and stiffness as predicted by EI for incised 24F-V4 Douglas Fir glued laminated timber beams of various widths[a]

	79.3 mm (3.125 in.)		130.2 mm (5.125 in.)		171.5 mm (6.75 in.)		222.3 mm (8.75 in.)	
Laminations	El	I	EI	I	EI	I	EI	I
6	0.896	0.812	0.924	0.858	0.932	0.872	0.936	0.879
8	0.909	0.833	0.934	0.877	0.942	0.891	0.946	0.898
10	0.916	0.844	0.940	0.887	0.948	0.901	0.953	0.909
12	0.921	0.854	0.945	0.896	0.953	0.910	0.958	0.919
14	0.925	0.860	0.948	0.901	0.956	0.916	0.961	0.924
16	0.928	0.865	0.951	0.906	0.958	0.920	0.963	0.929
18	0.930	0.869	0.953	0.909	0.960	0.924	0.965	0.932
20	0.932	0.872	0.954	0.912	0.962	0.926	0.967	0.935

“Normalized values were obtained using a reduced moment of inertia (I) to predict strength reduction and a complementary virtual work method to predict reduced bending stiffness (EI).

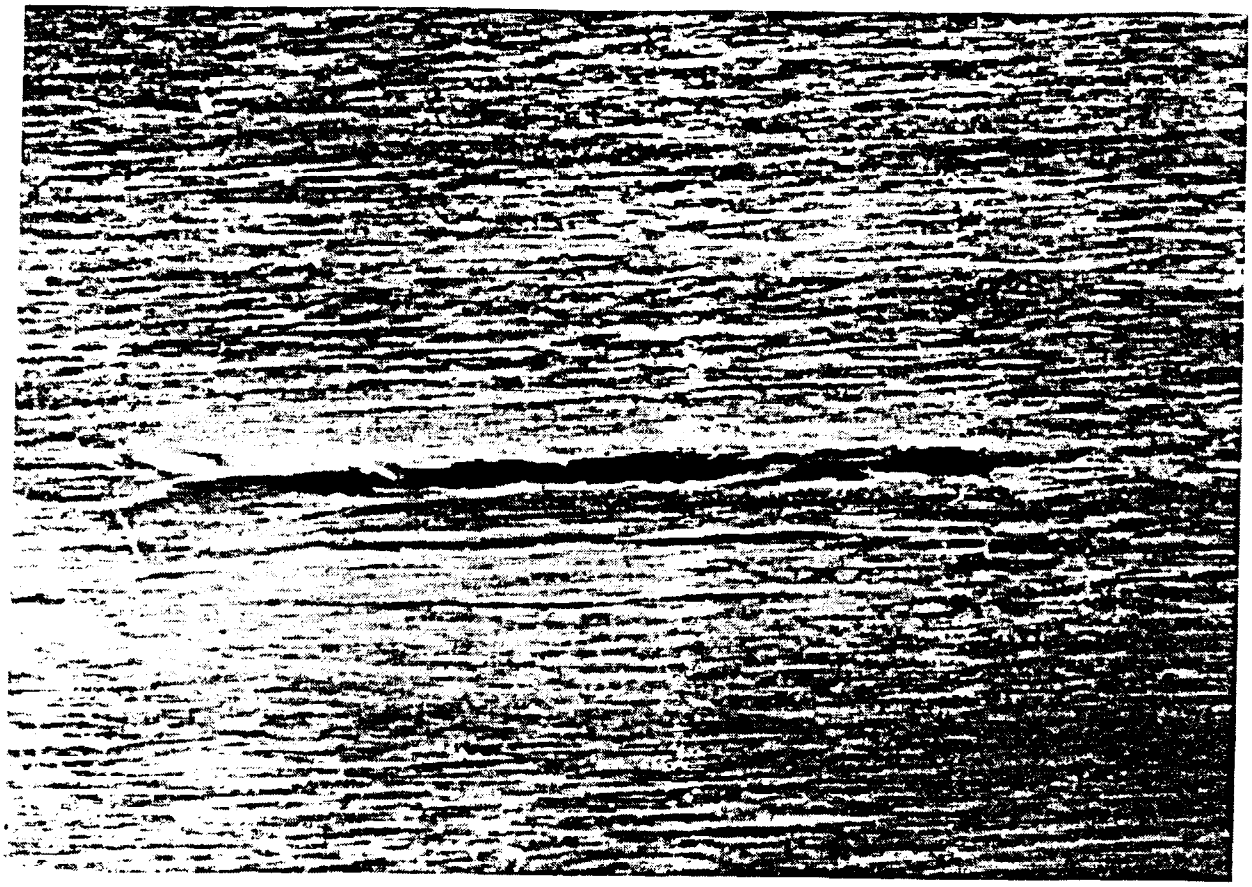

Figure 1-Top view of incision born a knife-like 5-mm-deep incision at an incision density of 8,500/m^2 into dry, Douglas Fir.

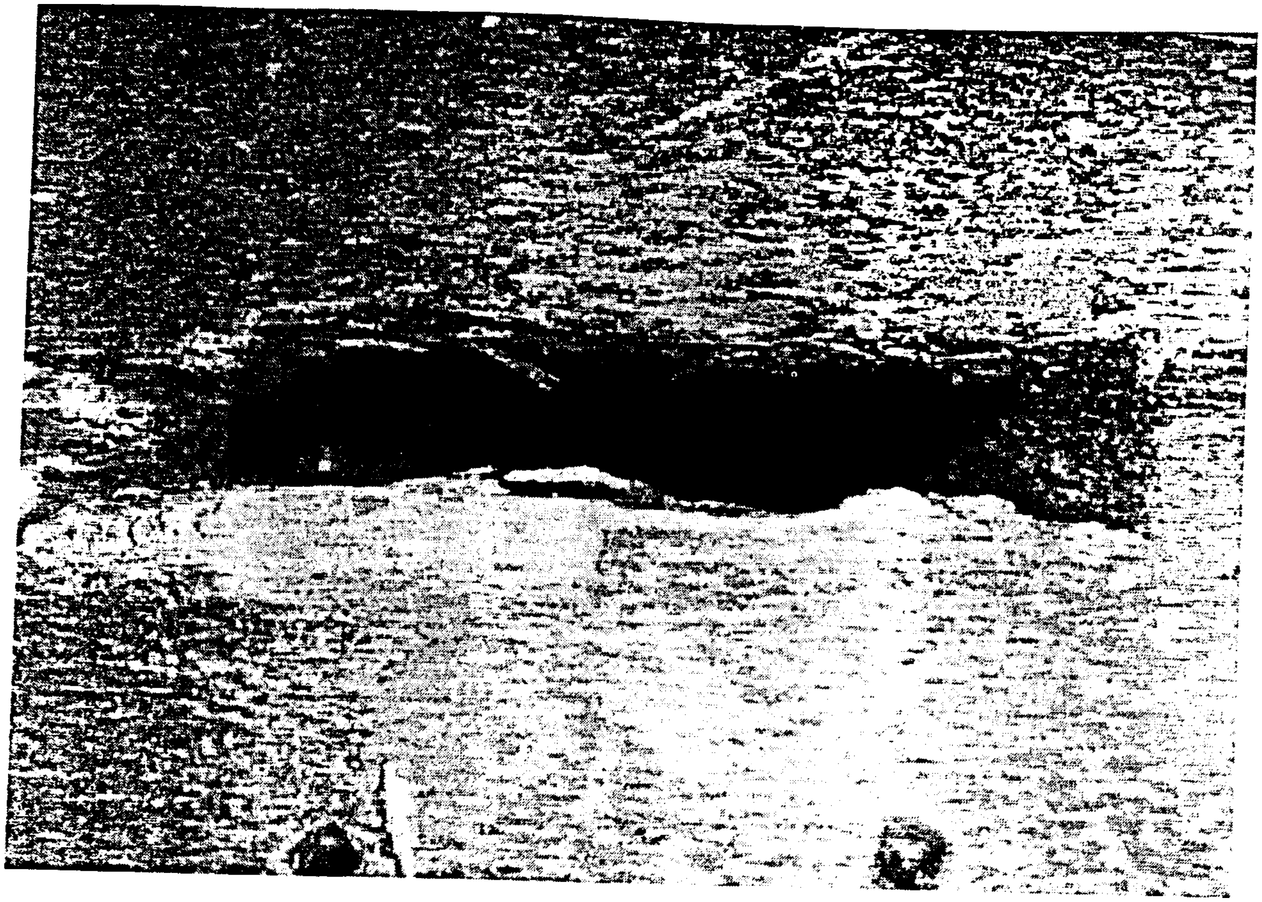

Figure 2-Top view of incision from a chisel-tooth 7-mm-deep incision at an incision density of 7,000/m^2 into dry Douglas Fir. Note additional damage at ends compared with Figure 1.

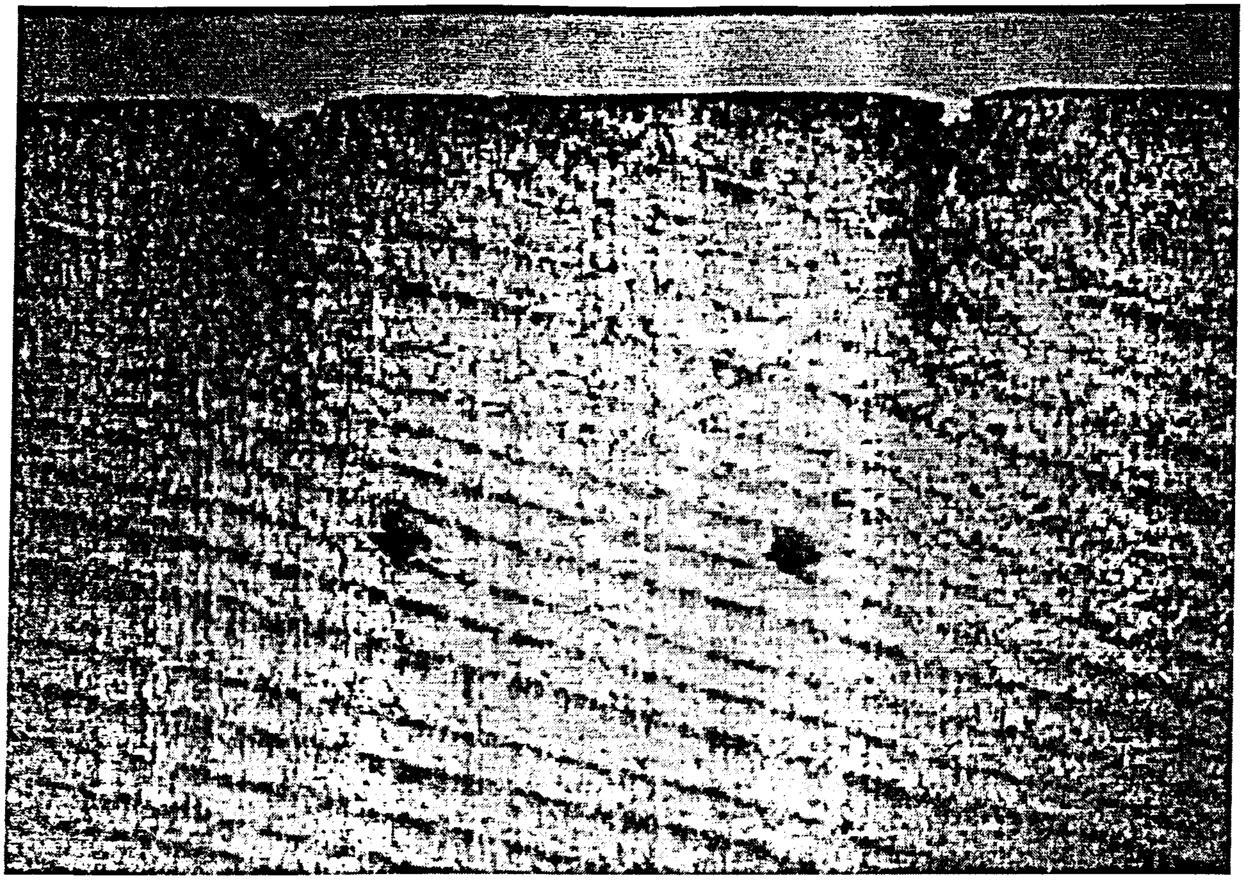

Figure 3-End view of incision from a knife-like 5-mm-deep incision at an incision density of 8,500/m^2 into dry Douglas Fir.

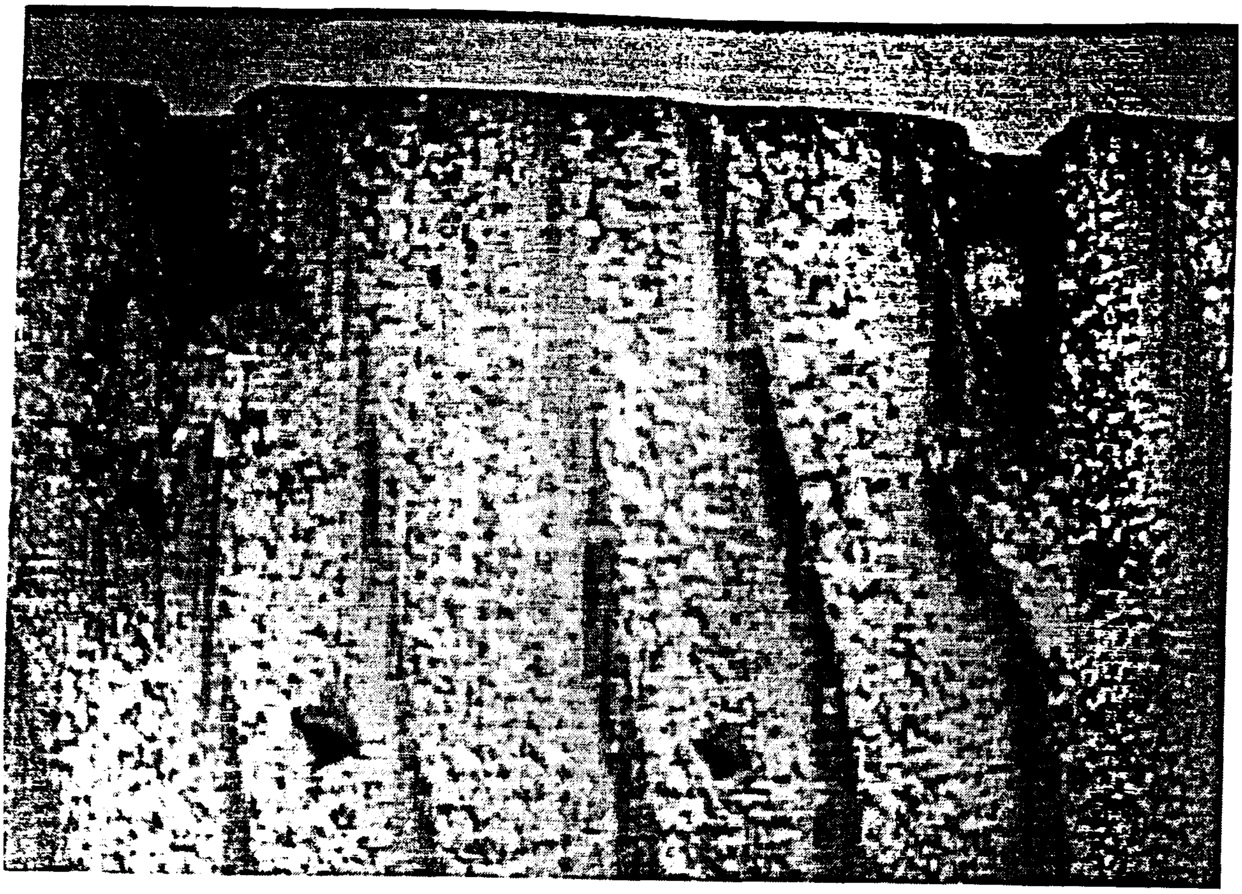

Figure 4-End view of incision from a chisel-tooth 7-mm-deep incision at an incision density of 7,000/m^2 into dry Douglas Fir. Note additional damage compared with Figure 3.

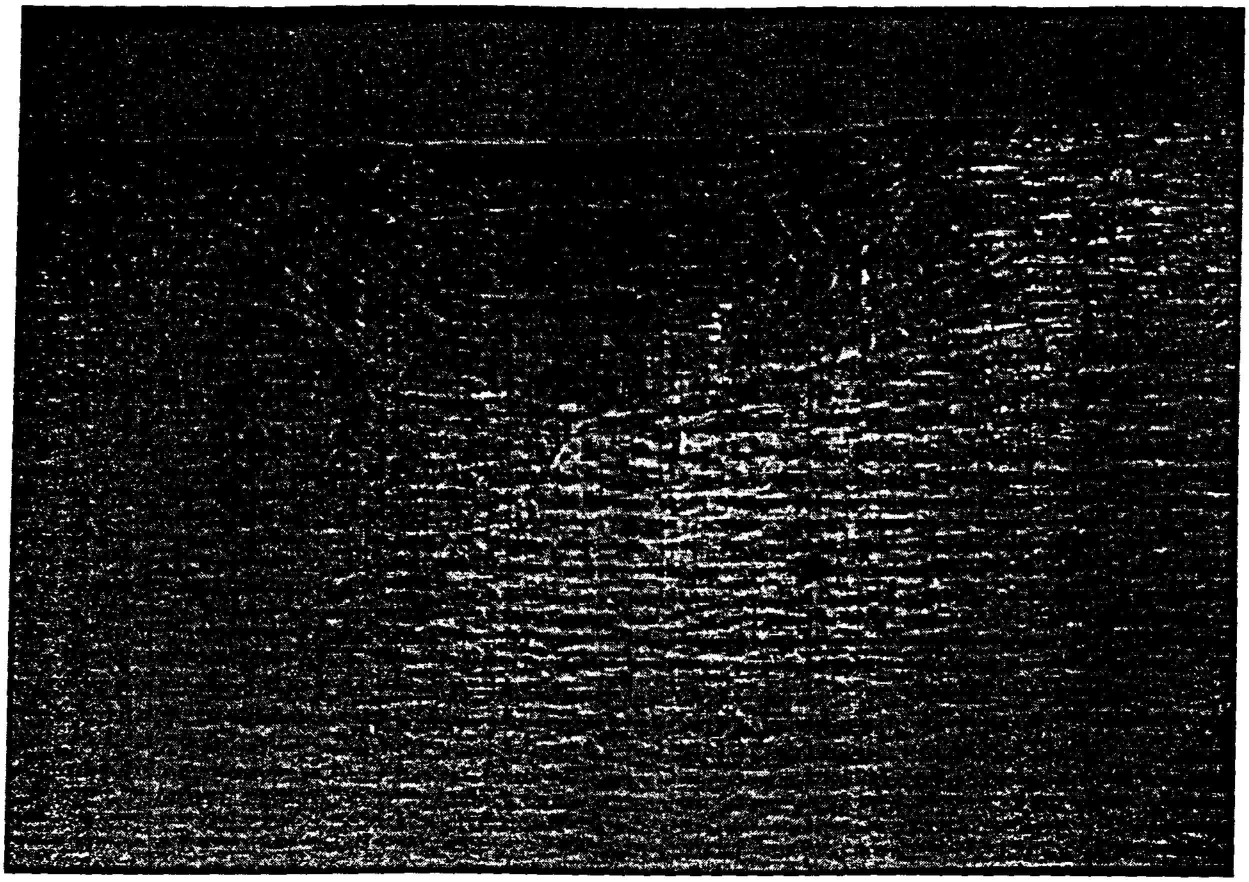

Figure 5-Close-up of the damage around and below a 5-mm-deep incision at an incision density of 7,000/m^2 into dry Douglas Fir.

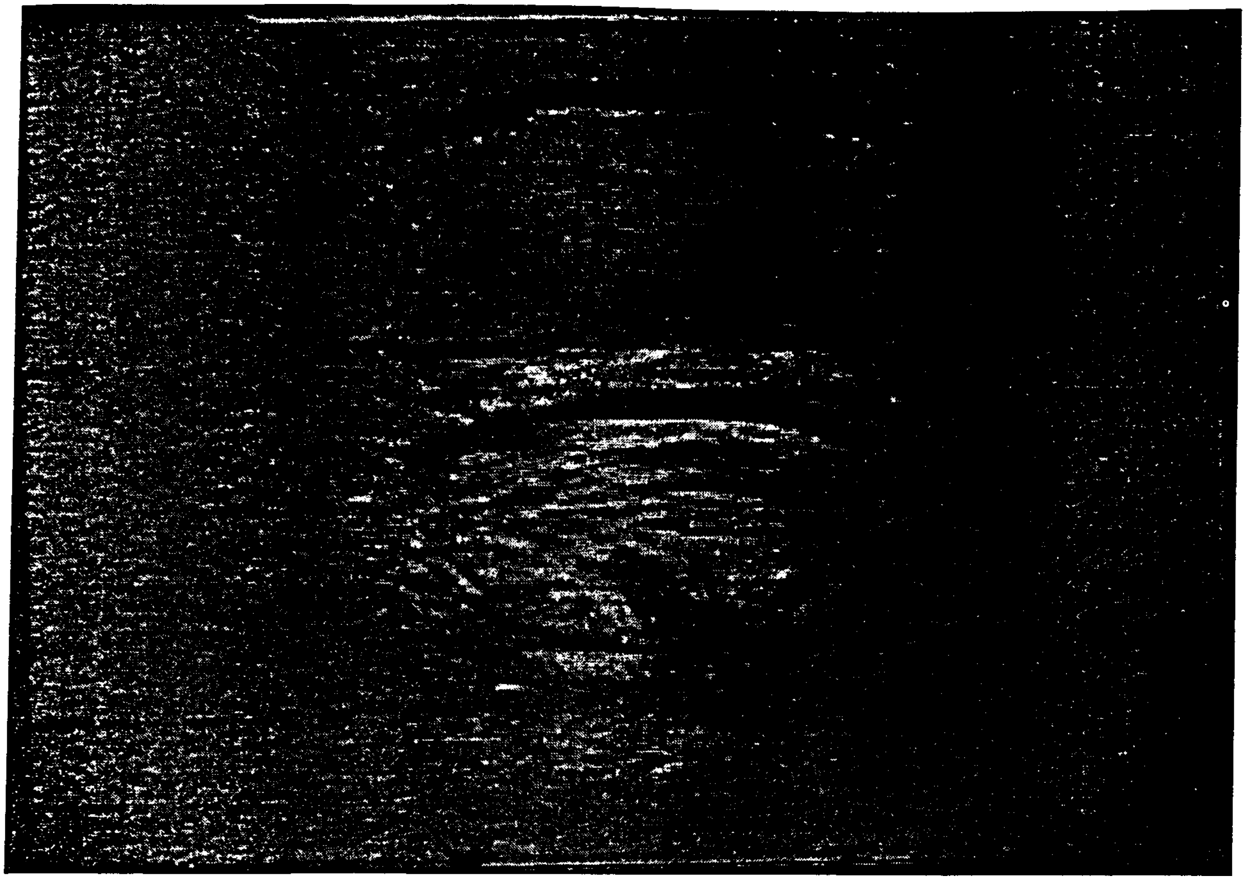

Figure 6-Close-up of the damage around and below a 7-mm-deep incision at an incision density of 7,000/m^2 into dry Douglas Fir. Note additional damage compared with Figure 5.

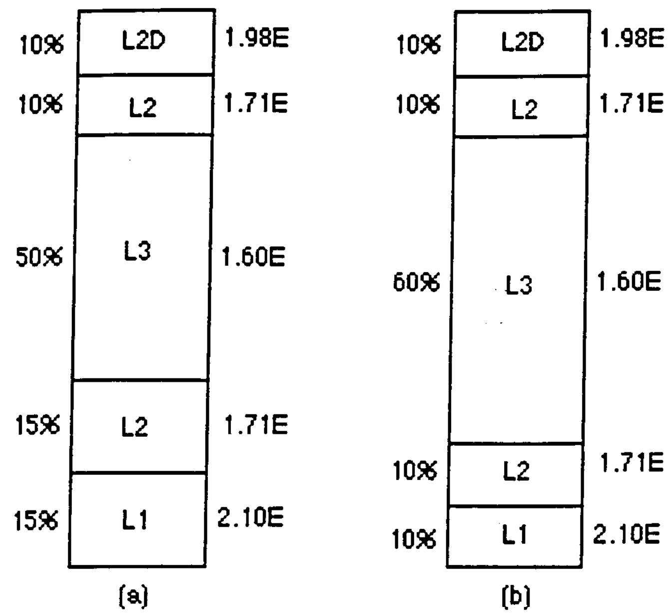

Figure 7-Lay-up combinations and individual lamination design properties for 24F-V4 glued laminated timber beams: (a) beams less than or equal to 381 mm (15 in.) deep, (b) beams greater than 381 mm (15 in.) deep.

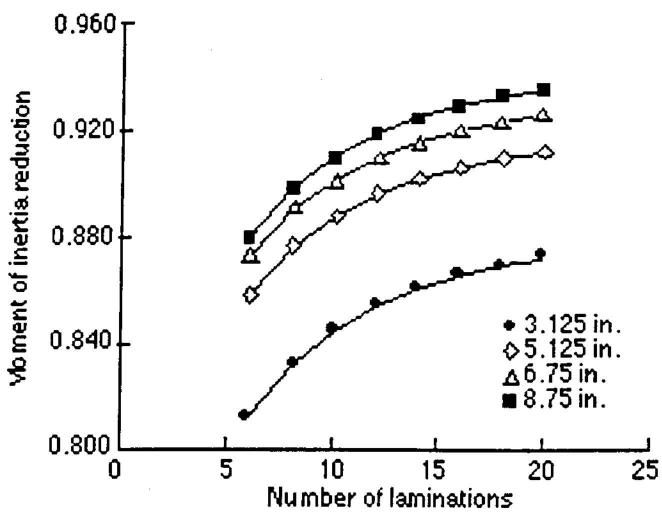

Figure 8-Predicted reduction in moment of inertia of 24F-V4 glued laminated beams due to incising (measurements are beam width).

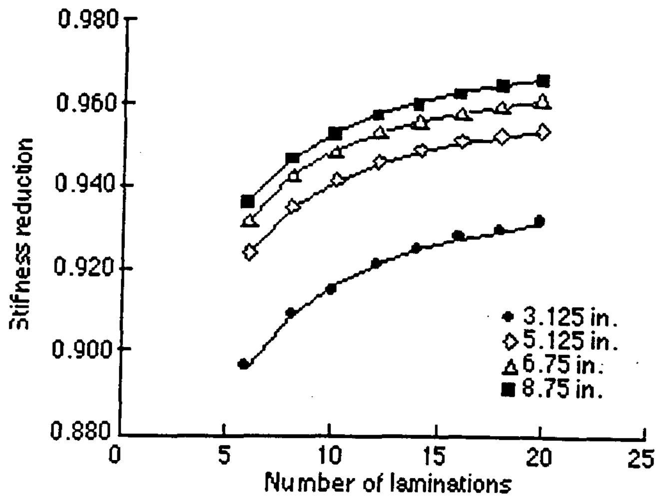

Figure 9-Predicted reduction in bending stiffiess of 24F-V4 glued laminated beams due to incising (measurements are beam width).

PROCEEDINGS

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