ANALYTICAL STUDIES ON THE NONLINEAR BENDING BEHAVIOR OF NAILED LAYERED COMPONENTS PART II. NAILED STRESSED-SKIN COMPONENTS

Fumio Kamiya

Forestry and Forest Products Research Institute
Ministry of Agriculture, Forestry and Fisheries
P.O. Box 16, Tsukuba Norin, Kenkyu Danchi-nai
Ibaraki 305, Japan

(Received October 1983)

ABSTRACT

The objective of this study is to develop a procedure for predicting the nonlinear bending behavior of the nailed stressed-skin component. This component might be regarded as a kind of nailed layered beam. When it is subjected to external loads, the direct forces in the plane of the plate are not uniformly distributed over the width of the plate. Because of this, the analytical procedure for predicting the nonlinear bending behavior of the nailed layered beam developed in the first part of this study is not applicable directly to the component. However, to use the concept of the effective breadth, assuming uniformly stressed width, instead of the actual width of the plate makes the procedure applicable to the nailed stressed-skin component. In other words, the component can be regarded as the nailed layered beam with the effective breadth. The effective breadth is obtained by Amana and Booth's theory (1967a, b). The experiments that were conducted to examine the validity of the procedure showed that it gave excellent agreements with the experimental results. The solution was used for investigating the effect of some parameter on the stiffness, and useful information for designing the component was given.

Keywords: Beams, fasteners, deformation, loads, nonlinear analysis.

INTRODUCTION

The nailed layered system is widely used in wood construction. However, it is complicated to analyze because of the nonlinear mechanical characteristics. The objective of this study is to develop an analytical procedure for predicting the nonlinear bending behavior of the nailed components. A basic theory of the nailed layered beam has been already presented by Kamiya (Tremblay et al. 1976) as the first part of this paper, and in this second part, the applicability of this procedure to the nailed stressed-skin component is investigated.

When stressed-skin units are subjected to external loads, the direct forces in the plane of the plate are not uniformly distributed over the width of the plate as shown in Fig. 1. This nonuniform distribution is termed shear lag. Because of this, the procedure for predicting the nonlinear bending behavior of the nailed layered beam is not applicable directly to the nailed stressed-skin component.

However, there is a convenient concept that might make the procedure applicable to the stressed-skin component. It is the effective breadth which is an assumptive uniformly stressed width. This concept is originally for the glued stressed-skin component and is hardly considered to use for the nailed component. But the development of the theory of the nailed layered beam might make the concept useful for the nailed stressed-skin component.

Series solution for the component with orthotropic plate presented by Amana and Booth (1967a, b) provides a background of calculating the effective breadth.

Wood and Fiber Science, 17(2), 1985, pp. 170–183

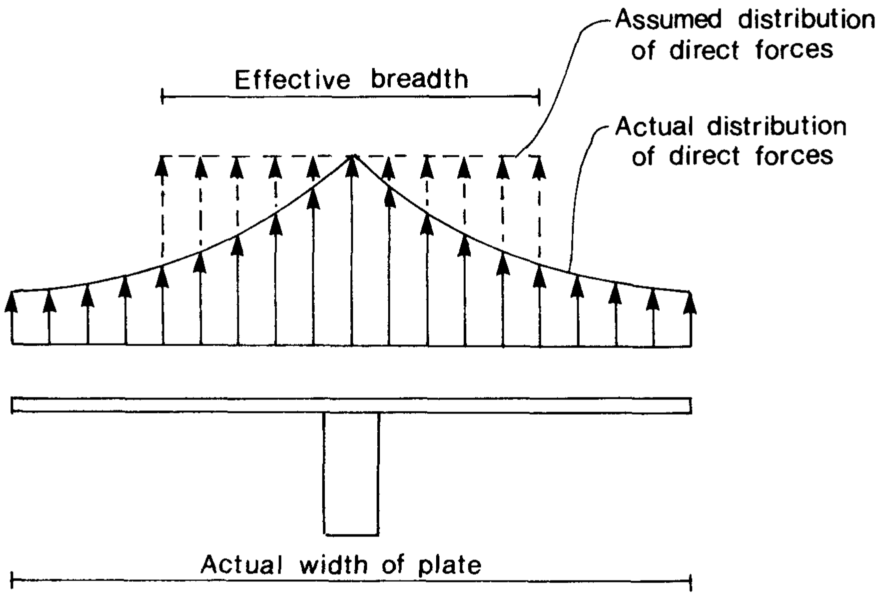

FIG. 1. Effective breadth.

In this theory, the concept of the slip modulus was used for the nailed component. Therefore, the calculated results show linear characteristics.

In order to investigate and extend this theory, many studies were conducted—among them, the parts about the slip modulus and the effective breadth that are important to develop this study are summarized.

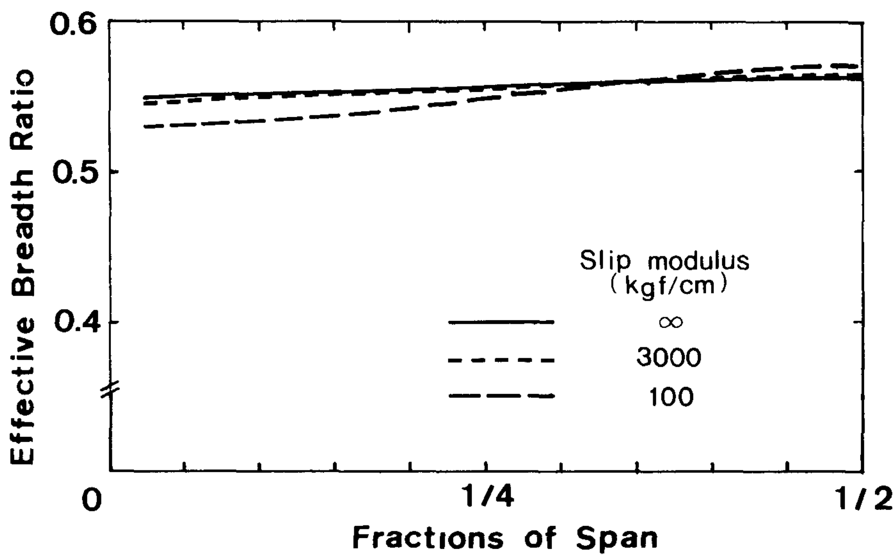

FIG. 2. Variation of effective breadth along the span and effect of slip modulus on effective breadth, for SD90F (cf. Table 1).

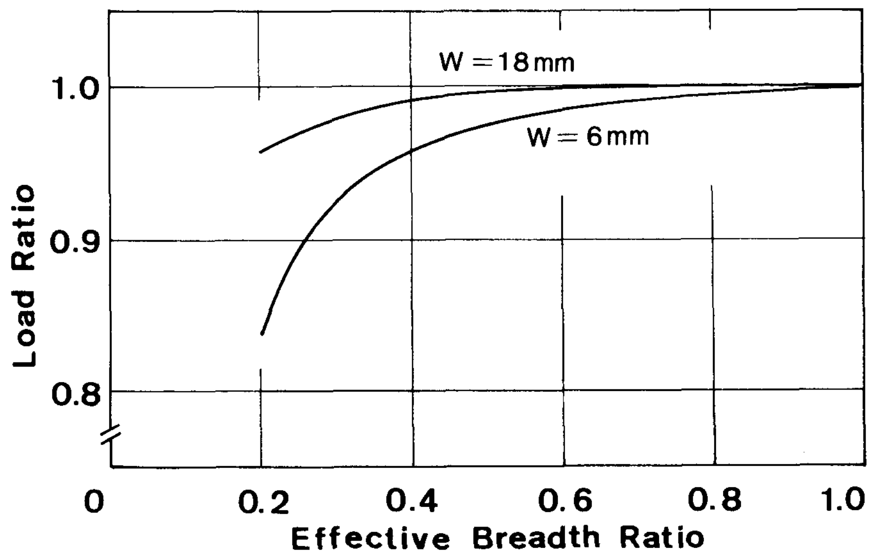

FIG. 3. Effect of effective breadth on stiffness of nailed component.

Effective breadth; Hirashima (1973) investigated the effect of some parameters on the stiffness and drew the charts of the effective breadth ratio in relation to the parameters. Maeda and Sawada (1981) investigated empirically the effective breadth of the nailed stressed-skin components by using electrical resistance strain gauges, and reported that the observed values of the effective breadth at the midspan agreed with the calculated results by Amana and Booth's theory. The same results were also reported by Ando and Sugiyama (1980). Furthermore, they reported that the effective breadth increased with increase in the distance from midspan and the observed effective breadth did not agree with the theoretical one except at the midspan.

Slip modulus and nail resistance; Maeda and Sawada (1981) calculated backwards the slip modulus from the observed stiffness by using the theory of Amana and Booth. The calculated slip moduli showed values several times as much as that predicted from the results of the nailed joint tests. They supposed that the reason was due to the nonlinear characteristic of the nailed joint. Ando and Sugiyama (1980) reasoned empirically that the nail forces distributed uniformly along the span.

THEORY

Preliminary investigation

In order to apply the theory of the nailed layered beam to the nailed stressed-skin component, the following conditions must be satisfied;

1. The effective breadth is constant along the span.
2. The effective breadth is not affected by the rigidity of the plate-rib joint.

The first condition is approximately satisfied by Amana and Booth's theory. The second condition is very important for this study because the objective is to

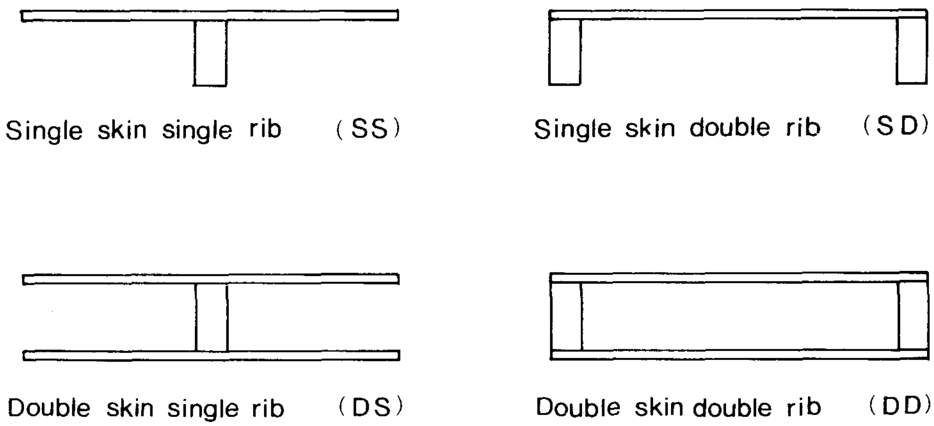

FIG. 4. Types of test specimens.

present a procedure for predicting the nonlinear bending behavior of the component due to the nonlinear load-slip characteristic of plate-rib joints. It seems to be extremely complicated to examine theoretically whether this condition is satisfied or not.

Although Amana and Booth's theory is based on the linear characteristic of the plate-rib joints, it might provide useful information to investigate the effect of

TABLE 1. *Test specimens.*

Specimen	Type	Nail spacing (mm)	Loading	Rib E_b (kgf/cm²)	Skin E_b (kgf/cm²)	Skin E_l (kgf/cm²)	Skin E_r (kgf/cm²)	Skin G (kgf/cm²)	Skin Effective breadth ratio
SS90C	SS	90	Central point	103,600	103,400	73,800	67,000	3,850	0.559
SS90F	SS	90	Two point	106,800	99,500	77,400	58,200	3,880	0.550
DS90F	DS	90	Two point	120,500	98,500	71,700	70,000	3,830	0.564
SD90C	SD	90	Central point	106,400	114,600	73,800	67,000	3,850	0.552
SD45F	SD	45	Two point	94,800	100,400	74,200	68,700	3,250	0.514
SD64F	SD	64	Two point	97,500	93,200	73,000	63,000	3,480	0.532
SD90F	SD	90	Two point	113,400	117,100	71,400	60,100	3,860	0.559
SD150F	SD	150	Two point	92,700	97,400	71,400	60,100	3,860	0.559
DD90F	DD	90	Two point	158,100	112,800	78,400	58,600	3,360	0.509

E_b: MOE in bending parallel to the face-grain.
E_l: MOE in compression parallel to the face-grain.
pu E_r: MOE in compression perpendicular to the face-grain.
G: Shear modulus.
1 mm = 0.0394 in.
1 kgf/cm² = 98.1 kPa = 14.2 psi.

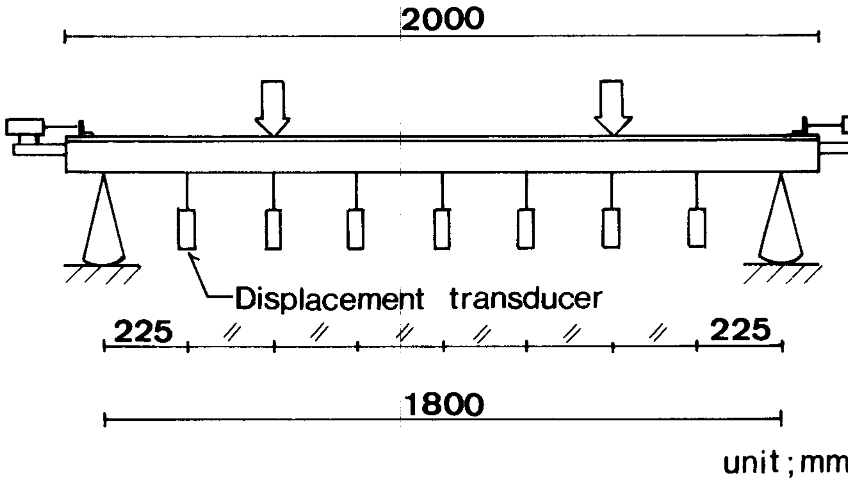

FIG. 5. Bending test of component, in case of two point loads.

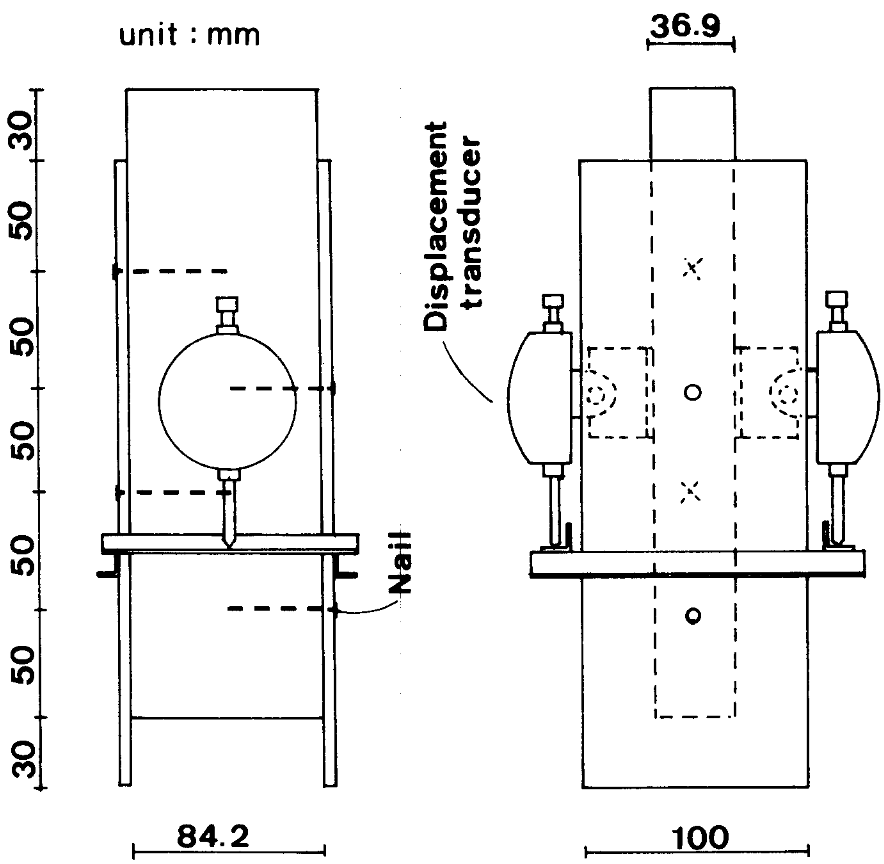

FIG. 6. Nailed joint test.

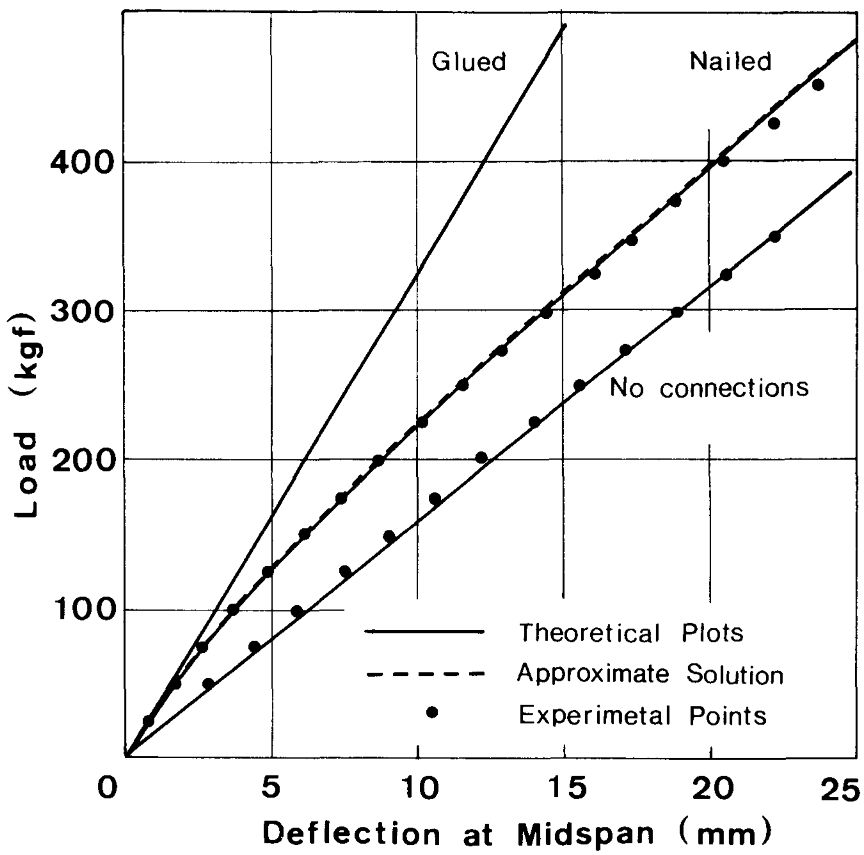

FIG. 7. Typical load versus deflection, for SS90C.

TABLE 2. *Comparison of calculated load with experimental load.*

Specimen	At W = 6 mm: Exp. load / Theo. load	At W = 6 mm: Exp. load / Approx. load	At W = 18 mm: Exp. load / Theo. load	At W = 18 mm: Exp. load / Approx. load
SS90C	1.00	1.00	0.99	0.99
SS90F	0.91	0.90	0.92	0.92
DS90F	1.08	1.07	1.04	1.03
SD90C	1.00	1.00	0.99	0.99
SD45F	1.01	0.98	0.97	0.96
SD64F	1.02	1.00	1.00	0.99
SD90F	0.99	0.99	1.00	1.00
SD150F	1.00	0.99	1.01	1.01
DD90F	1.01	1.00	0.96	0.95
(Ave.)	1.00	0.99	0.99	0.98

W = Deflection at midspan.
1 mm = 0.0394 in.

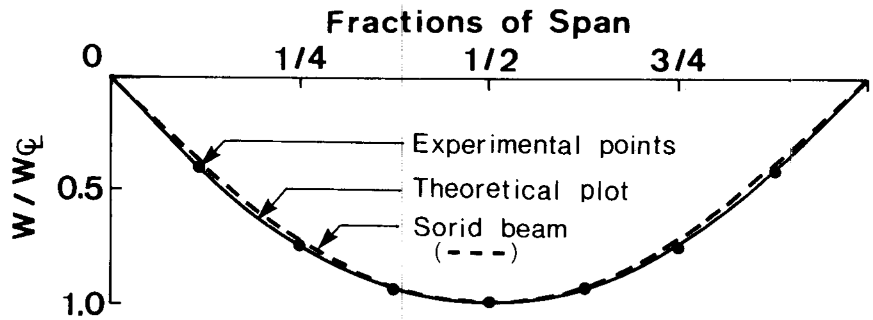

FIG. 8. Typical deflection curve, for SD90F at P = 450 kgf.

the slip modulus on the effective breadth by using their theory. Figure 2 shows the result of this investigation. In this figure, it can be seen that the effective breadth is hardly affected by the slip modulus and is almost constant along the span. From this investigation, it was assumed that the conditions were approximately satisfied.

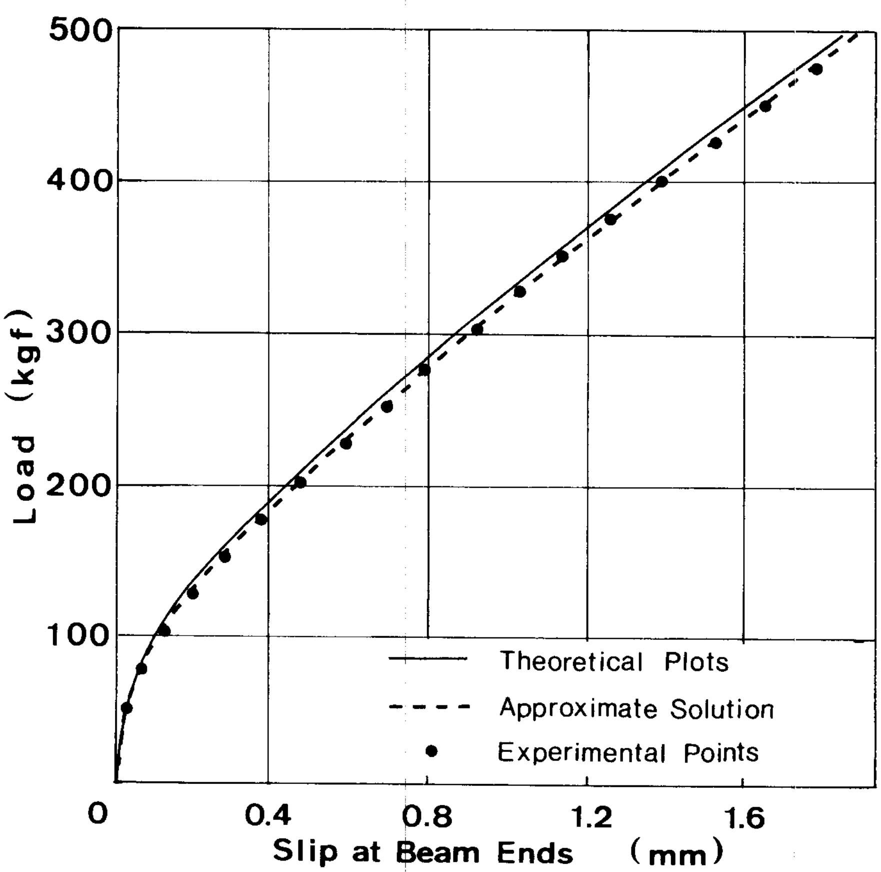

FIG. 9. Typical load versus slip at beam ends, for SS90C.

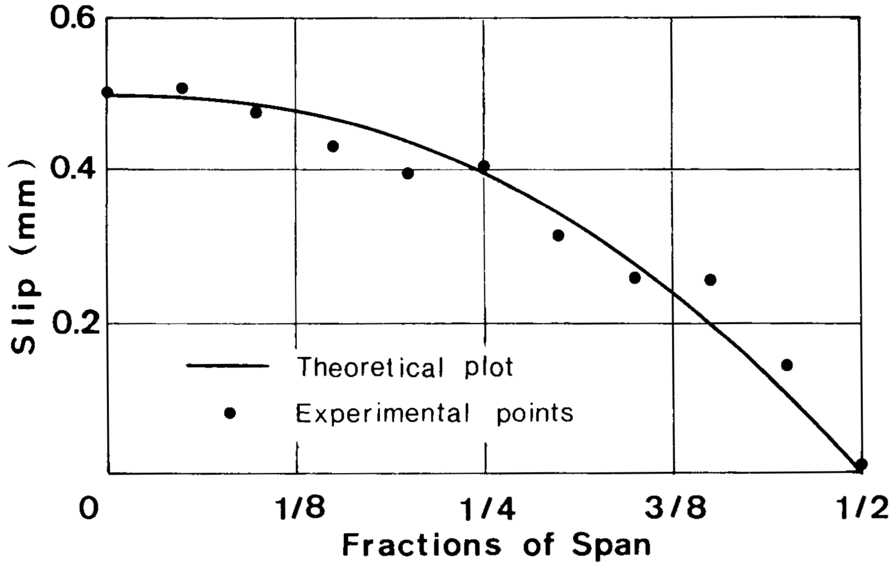

FIG. 10. Typical slip distribution along the span, for SD90C at P=500 kgf.

The stiffness of the nailed stressed-skin component is not affected by the effective breadth as much as the glued component because of the incomplete interaction. Figure 3 shows an example of the effect of the effective breadth on the stiffness of the nailed stressed-skin component, which is obtained by the procedure de-

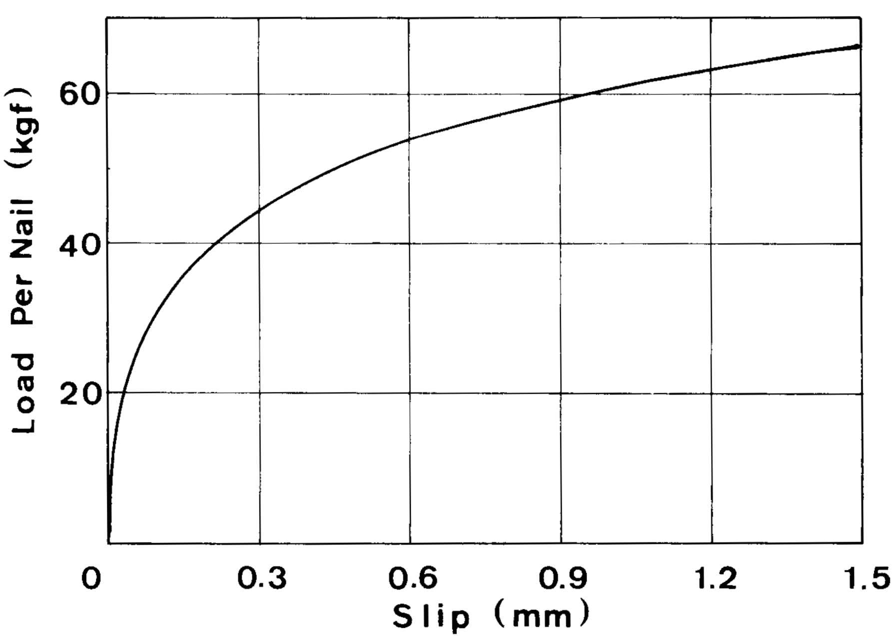

FIG. 11. Load-slip characteristic for a single nail used in the numerical experiments.

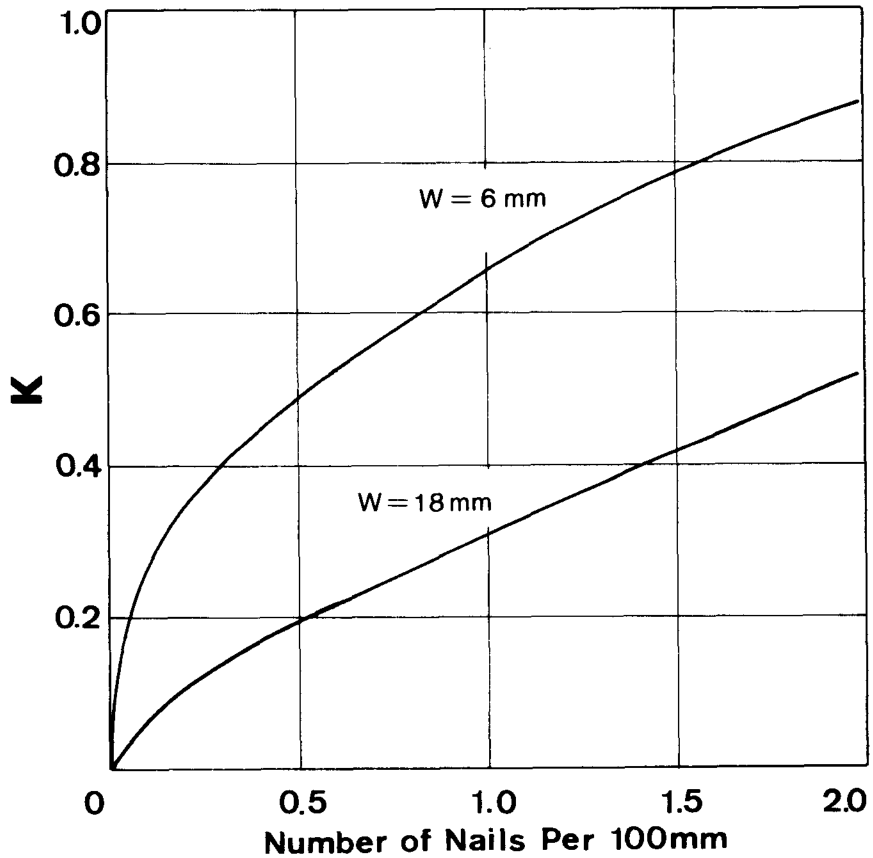

FIG. 12. Effect of number of nails on K.

veloped in this study. In case of this component, doubling effective breadth ratio from 0.5 to 1.0 produces an increase in the load at the indicated deflection of less than 5%.

CALCULATING PROCEDURE

The nailed stressed-skin component can be regarded as the nailed layered beam with effective breadth. If the effective breadth is used instead of the actual width of the plate in calculating the area of skin, all equations for the nailed layered beam developed in the first part of this study can be applied to the nailed stressed-skin component. The reason that the effective breadth is used in the calculation of the area of skin is that the term of the area is concerned with the direct forces. In calculating the second moment of area of skin, the actual width should be used.

It is sufficient to use the effective breadth of the glued component as that of the nailed component. It can be obtained by Amana and Booth's theory.

For the single skin type.—The equations for the two-layered beam are applied.

For the double skin type.—The equations for the three-layered beam are applied.

For the double or multiple rib type.—These types of component may be regarded as a series of linked I or T-beams. Therefore, it may be sufficient to calculate one such unit.

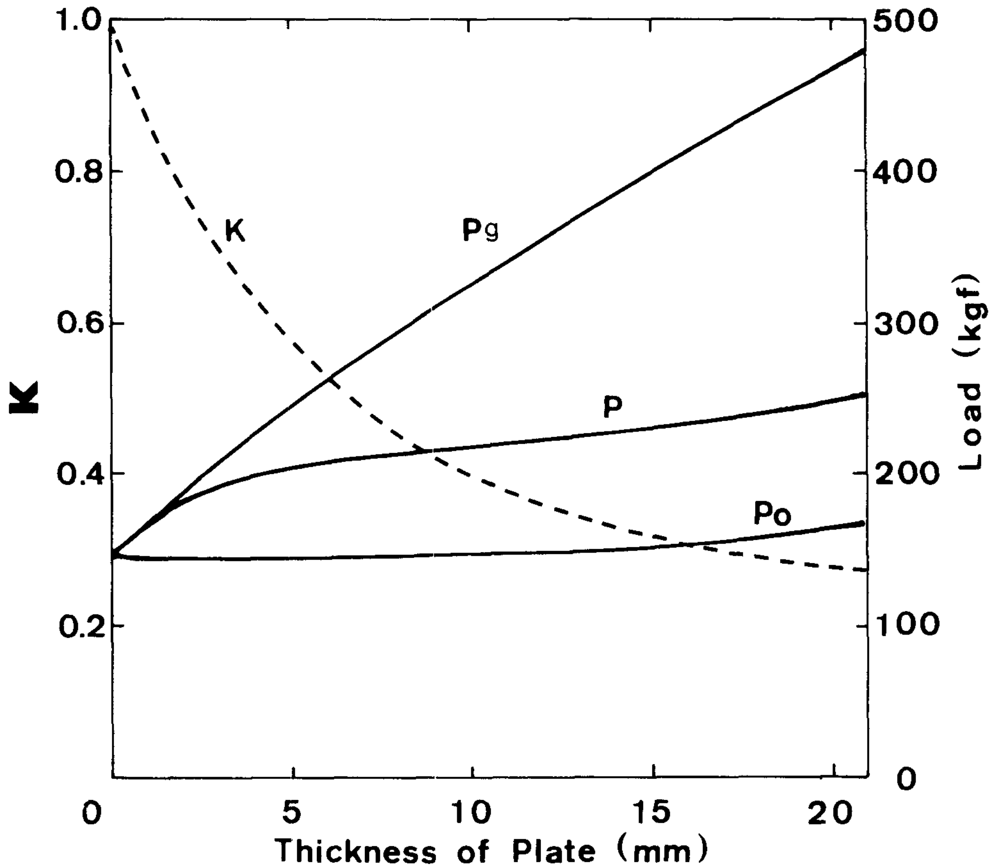

FIG. 13. Effect of thickness of plate on stiffness.

EXPERIMENTS

Test specimens and testing method

Four types of nailed stressed-skin components as shown in Fig. 4 and Table 1 give the specimen information which was tested to examine the validity of the procedure.

The rib was selected from kiln-dried 2 by 4 western hemlock, and was planed again to reduce the effect of friction at the contact surfaces. The finished cross section was 36.9 mm by 84.2 mm. The nominal 7.5-mm-thick Lauan plywood was used as skin. The actual thickness was 7.9 mm and the width was 450 mm. The plywood was placed over ribs with the face-grain of the plywood parallel to length of the rib. The nail used was CN50, which is defined in JIS A5551, and is almost equal to the 6d common nail in the USA.

The central point load or the two point loads were applied to the components with 1800-mm span as shown in Fig. 5. The deflection at each point divided the span into eight equal lengths and the slip displacement at the beam ends was measured by displacement transducers.

The special instrument which had been used in the first part of this study was used again to measure the slip displacement of each nail.

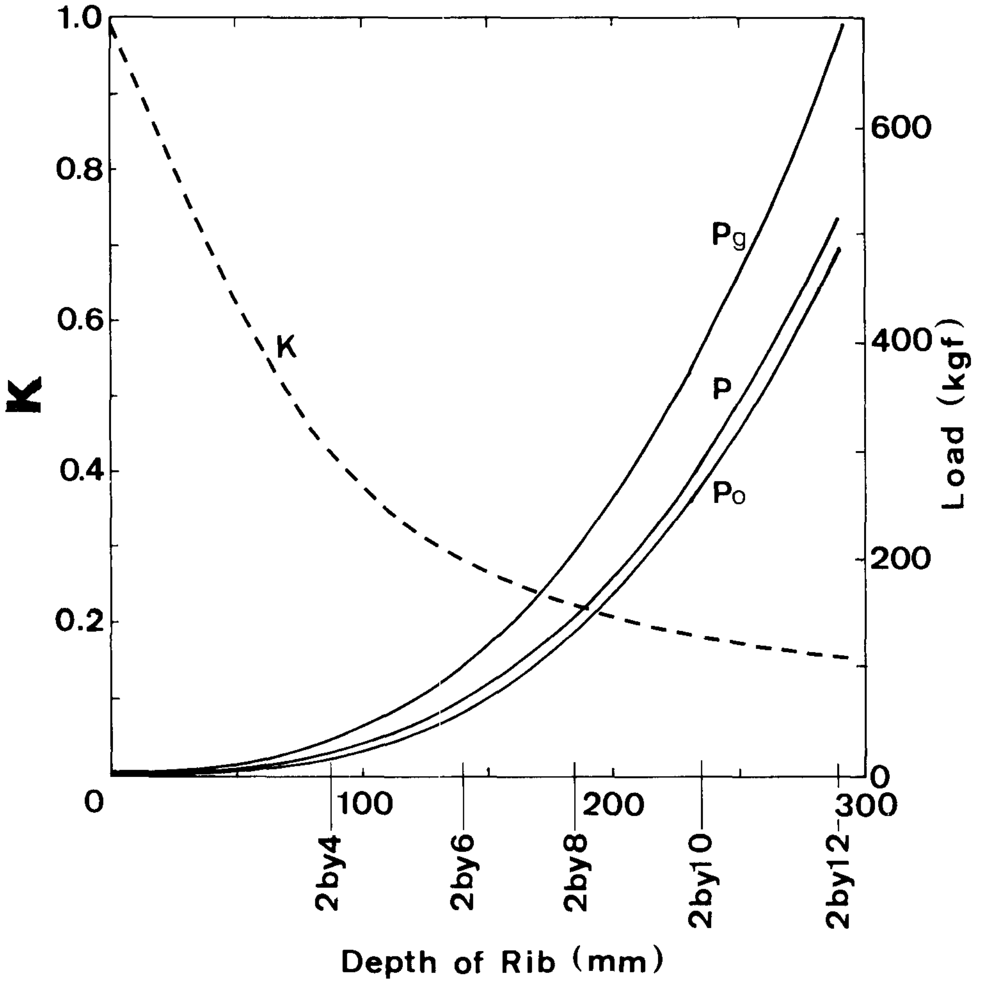

FIG. 14. Effect of depth of rib on stiffness.

The load-slip characteristics for a single nail were obtained by the nailed joint test as shown in Fig. 6. The Young's moduli of the plywood were obtained by the compression test.

Comparison of calculated results with experimental results

Deflection.—Figure 7 shows the typical load-deflection curves. Comparison shows that the calculated results including the approximate solution agree with the experimental results. This can be seen for the other test specimens. For all test specimens, the ratio of experimental load to calculated load when the deflection at midspan is 6 mm (L/300) or 18 mm (L/100) was shown in Table 2. From this table, we can see that both calculating procedures predict well the nonlinear bending stiffness of the nailed stressed-skin component.

Figure 8 shows a typical deflection curve along the span. The deflection curve of the nailed stressed-skin component is almost equal of the solid beam. The calculated curve agrees well with the observed result.

Slip of nail.—Figure 9 shows a typical load-slip at the beam ends curve and Fig. 10, the slip distribution along the span. The good agreements of the calculated results with the experimental results show that the calculating procedures can also predict well the slip displacement at the contact surfaces of the nailed stressed-skin component.

NUMERICAL EXPERIMENTS

It might be useful for the design of the component to investigate the effects of various parameters on the bending behavior of the component. The solutions are now used to study their effects on the behavior.

Excellent investigation on the effect of some parameter on the effective breadth has been already conducted by Amana and Booth. Therefore, in this study, attention is focused on the particular aspect of the effect caused by the nonlinear characteristics of the nailed joints.

Except where specified otherwise, the results apply to the single-rib single-skin component for the following parameters and conditions.

Skin: thickness = 9 mm, breadth = 450 mm, effective breadth ratio = 0.55, MOE in bending = 90,000 kgf/cm^2, MOE in compression (span direction) = 70,000 kgf/cm^2.

Rib: depth = 89 mm, breadth = 38 mm, MOE = 90,000 kgf/cm^2.

Nailing: nail = CN50, spacing = 90 mm.

Loading: two point, span = 1,800 m.

The load-slip curve for a single nail used in this study is shown in Fig. 11. This curve is assumed to be independent of the thickness of plate and the depth of rib and is approximated by the composition of fourteen connected straight lines.

The following factor might express well the contribution of the connectors to the stiffness of the component:

$$K = \frac{P - Po}{Pg - Po}$$

where P, Pg and Po are, respectively, the load of the nailed component, of the glued component and of the no connections component corresponding to the same deflection.

When there is no connection, K is zero. When there are infinite multitude of connectors, K reaches its maximum value, 1. If K is 0.5 for example, this means that the resistance of the nailed component is just middle between that of the no connections component and that of the glued component for the same deflection. K is the factor that varies depending on the corresponding deflection because of the nonlinear characteristic of the nailed joint.

Figure 12 shows the effect of the number of nails on K. In case of this component, an increase in the number of nails per length 100 mm of beam from 0.5 (spacing = 200 mm) to 2.0 (spacing = 50 mm) produces an increase in K for deflection 6

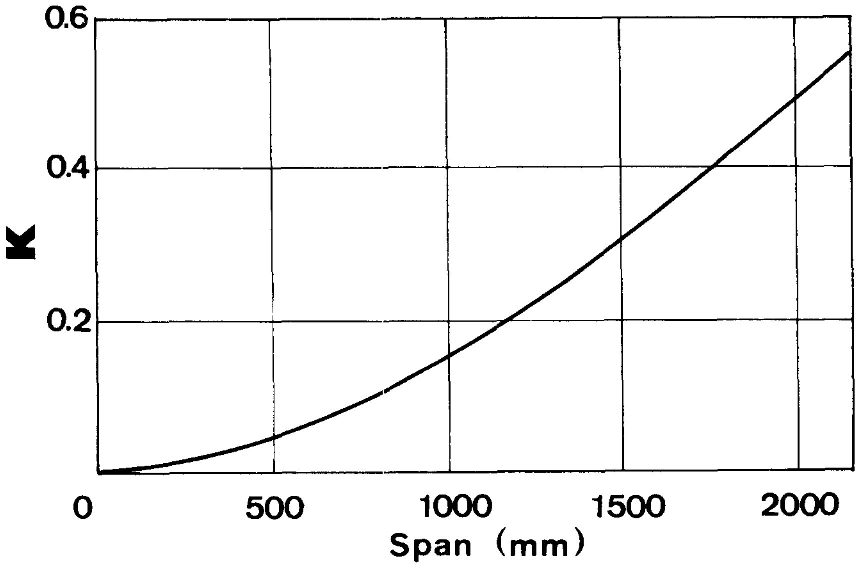

FIG. 15. Effect of span on stiffness.

mm from 0.49 to 0.88, an increase of 0.39, and for deflection 18 mm from 0.19 to 0.52, an increase of 0.33.

Figure 13 shows the effect of the thickness of plate on the load and K when the deflection is 6 mm. An increase in the thickness of plate produces a comparatively remarkable rise in the load of glued component. This results in a reduction in K. From Figs. 12 and 13, we can see that the increase of the number of nails has greater effect on the stiffness than the increase of thickness of plate.

Figure 14 shows the effect of the depth of rib on the load and K when the deflection is 6 mm. As the depth of rib increases, the load of nailed component increases. This is mainly due to the increase in the second moment of area of rib. In fact, an increase in the depth produces a decrease in K. The increase in the second moment of area of rib produces also a decrease in the ratio of the second moment of area of plate to that of rib, which results in the decrease in the stressed-skin effect. Because of this, for the component with large depth rib, enlargement of K by reinforcement of plate-rib joints gives slight effect on the stiffness. For such a component, both reinforcement of plate-rib joints and increase of thickness of plate are needed to increase the stressed-skin effect.

Figure 15 shows the effect of the length of span on K when the deflection is 6 mm. From this figure, we can see that the contribution of connectors increases as the span becomes long.

CONCLUSIONS

The analytical procedures including the approximate procedure for predicting the nonlinear bending behavior of the nailed layered beam developed in the first part of this paper were applied to the nailed stressed-skin component. In the calculation, the effective breadth was used instead of the actual width of plate. The effective breadth was obtained by Amana and Booth's theory.

Experiments were conducted to examine the validity of the procedures and showed that both procedures gave excellent agreement with the experimental results.

The solution was used for investigating the effect of some parameter on the stiffness. The following results were given; In order to strengthen the stiffness, it is enough to increase the number of nails for the component with comparatively small-depth ribs. However, for the component with large-depth ribs, thickening of plate is needed besides the increase of the number of nails.

REFERENCES

AMANA, E. J., AND L. G. BOOTH. 1967a. Theoretical and experimental studies of nailed and glued plywood stressed-skin components: Part I, Theoretical study. J. Inst. Wood Sci. 4(1):43–69.

AMANA, E. J., AND L. G. BOOTH. 1967b. . . . Part II, Experimental study. J. Inst. Wood Sci. 4(2): 19–34.

ANDO, N., AND H. SUGIYAMA. 1980. Flexural properties of stressed-skin panels with nailed plywood skin. J. Japan Wood Res. Soc. 26(10):679–685.

DAWSON, P. R., AND J. R. GOODMAN. 1976. Variability simulations of wood joist floor systems. Wood Sci. 8(4):242–251.

GOODMAN, J. R., M. C. VANDERBILT, M. E. CRISWELL, AND J. BODIG. 1974. Composite and two-way action in wood joist floor systems. Wood Sci. 7(1):25–33.

HIRASHIMA, Y. 1973. Study on bending of wooden stressed-skin panels. Bulletin of the Government Forest Experiment Station No. 255:1–21.

KAMIYA, F. 1984. Analytical studies on the nonlinear bending behavior of the nailed layered components: Part I, Nailed layered beams. Wood Fiber Sci 17(1):117–131.

MAEDA, N., AND M. SAWADA. 1981. Stiffness and stress distribution of wooden stressed-skin panels in bending. Research Bulletins of the College Experiment Forests Hokkaido University 38(1):99–120.

TREMBLAY, G. A., J. R. GOODMAN, AND M. E. CRISWELL. 1976. Nonlinear analysis of layered T-beams with interlayer slip. Wood Sci. 9(1):21–30.