An Experimental Study on Use of Glued Laminated Timber for Bridge Beams

K. G. TAMBERG AND M. W. HUGGINS
Research Assistant and Associate Professor, respectively, Department of Civil Engineering University of Toronto

The testing program reported here was sponsored by the Ontario Department of Highways and undertaken to supply certain information that will allow design engineers to utilize glued laminated timber in bridges more efficiently. Past investigation had not adequately clarified the effects of scarf profile, scarf patterns, and delamination on the strength properties of creosoted laminated beams in flexure.

This program, although limited by time and available financing, attempted to (a) study the effects of two types of scarf profile, (b) study the effect of three types of scarf patterns, and (c) provide pilot tests for the effects of delamination on creosoted laminated beams. For objectives (a) and (b) 81 beams were used, all 16 ft long, about 5¼ in. wide, and built up of 16 laminations. For objective (c) 70 beams, 9 ft long, 3 in. wide, and built up of eight ¾-in. laminations, were used.

Beams of the larger group, all 16 ft long, were loaded symmetrically at points 6 ft apart. Load points and reactions were provided with knife edges and bearing plates. Load deflection readings were taken to ultimate failure.

The 70 smaller beams (objective c) were all tested by mid-point loading.

Moisture content of the specimens was measured with an electric resistance-type moisture meter.

Analysis of the results led to several significant conclusions and indications, but at the same time established the desirability of further test programs.

• THE TESTING PROGRAM reported in this paper was conducted at the University of Toronto under the sponsorship of the Ontario Department of Highways as part of the Ontario Joint Highway Research Program. The test specimens were built by a well-established and competent fabricator of glued laminated timber and were creosoted.

The testing program was undertaken to contribute to the available information and to allow the designing engineer to design glued laminated timber for bridge beams with greater accuracy. Past work in laminated timber has not adequately clarified the effects of scarf profile, scarf pattern and delamination on the strength properties of creosoted laminated beams subjected to flexure. As a consequence, this project was undertaken. Time available did not permit a more extensive testing program.

The purposes of the experiment were as follows:

1. To investigate the effects of two types of scarf profile on the strength properties of creosoted laminated beams.
2. To investigate the effects of three types of scarf pattern on the strength properties of creosoted laminated beams.
3. To perform pilot tests on the effects of delamination on the strength properties of laminated beams.

DESIGN OF EXPERIMENT

In all, 151 beams were tested, the test beams being subdivided into two major sections. The first of the two sections comprised a total of 81 creosoted beams

and was tested primarily to investigate the effects of scarf profile and scarf pattern on the strength properties of the beams. These 81 beams in turn were subdivided into 8 groups. Figure 1 shows the details for 71 of the 81 specimens. The remaining 10 beams were more or less randomly assembled by the manufacturer, each beam being characterized by its own scarf pattern, and the details are not presented in this paper. The 81 test beams were 16 ft long, about 5¼ in. wide, and built up of 16 laminations. The second section consisted of 70 beams and was tested to investigate the effects of delamination. These beams were subdivided into 14 subgroups (Fig. 2) and were 9 ft long, 3 in. wide, built up of eight ¾-in laminations.

Referring to Figure 1, the first number describes the pattern of end joints, the letter describes the scarf profile and thickness of lamination, and the final number denotes the beam in the group. Typical examples are as follows:

1. Mark 0-A-1 to 10 signifies no end joints, built-up beams of 16 ⅝-in. laminations, and a total of 10 control beams.
2. Mark 1-A-1 to 11 signifies beams containing joint pattern 1, hooked feathered scarfs, built up of 16 ⅝-in. laminations, the group containing a total of 11 beams.
3. Mark 2-B-1 to 10 signifies beams containing joint pattern 2, hooked scarfs with end steps, built up of 16 ¾-in. laminations, the group containing a total of 10 beams.

The following beams were tested:

0-A-1 to 10	0-B-1 to 10
1-A-1 to 11	
2-A-1 to 10	2-B-1 to 10
3-A-1 to 10	3-B-1 to 10
B-1 to 10	

All beams except B-1 to 10 and the control beams contained scarfs of slope 1 in 12. Beams B-1 to 10 were built up of 16 ¾-in. laminations and contained hooked scarfs of slope 1 in 10; 5 of the beams, B-6 to 10, in addition contained butt joints.

The two types of scarf profile investigated are in common use, but it has been suspected for some time that the end step in scarfs of profile B exerts a stress concentrating effect and is the cause of premature failure in members subjected to flexure.

The three types of scarf pattern shown in Figure 1 were chosen to create a reasonably severe condition as far as the influence of scarf pattern on the flexural strength of a beam is concerned. Pattern 3 is similar to a pattern which had been specified in the design of a bridge. The spacing of scarfs in adjacent laminations was approximately 38.5 t and 32 t for ⅝-in. and ¾-in. laminations, respectively, where t=lamination thickness.

All beams, except group B-1 to 10, were built up of Laminating Grades B and C close-grained lumber (Fig. 1). Beams B-1 to 10 were built up of a mixture of Laminating Grades A, B, C and D, the outermost laminations of these beams containing Grade C and better. All of the beams were manufactured according to the "Canadian Standards Association Specification 0122-1953 for Glued-Laminated Timber Construction." The choice of grade was governed by the fact that Laminating Grades B and C are in common use.

The resorcinol-formaldehyde glue (Lauxite RF 900) used for bonding purposes was applied and treated according to the manufacturer's recommendations and past experience at the plant. To facilitate the glue application and assembly, three staples were allowed in each scarf joint to hold the joined pieces in place. The scarfs were brush spread by hand. All glue lines were characterized by a double spread and the total amount of glue applied was 80 lb per 1,000 sq ft of glue line. The glue used was chosen because of its resistance to moisture and preservative treatment.

The Rueping process was employed for creosoting purposes. A treatment of 8 pcf was used. Incising was not permitted because of its strength-reducing characteristics.

Referring to Figure 2, the numbers 1, 2, and 3 signify scarf patterns; a, c and d

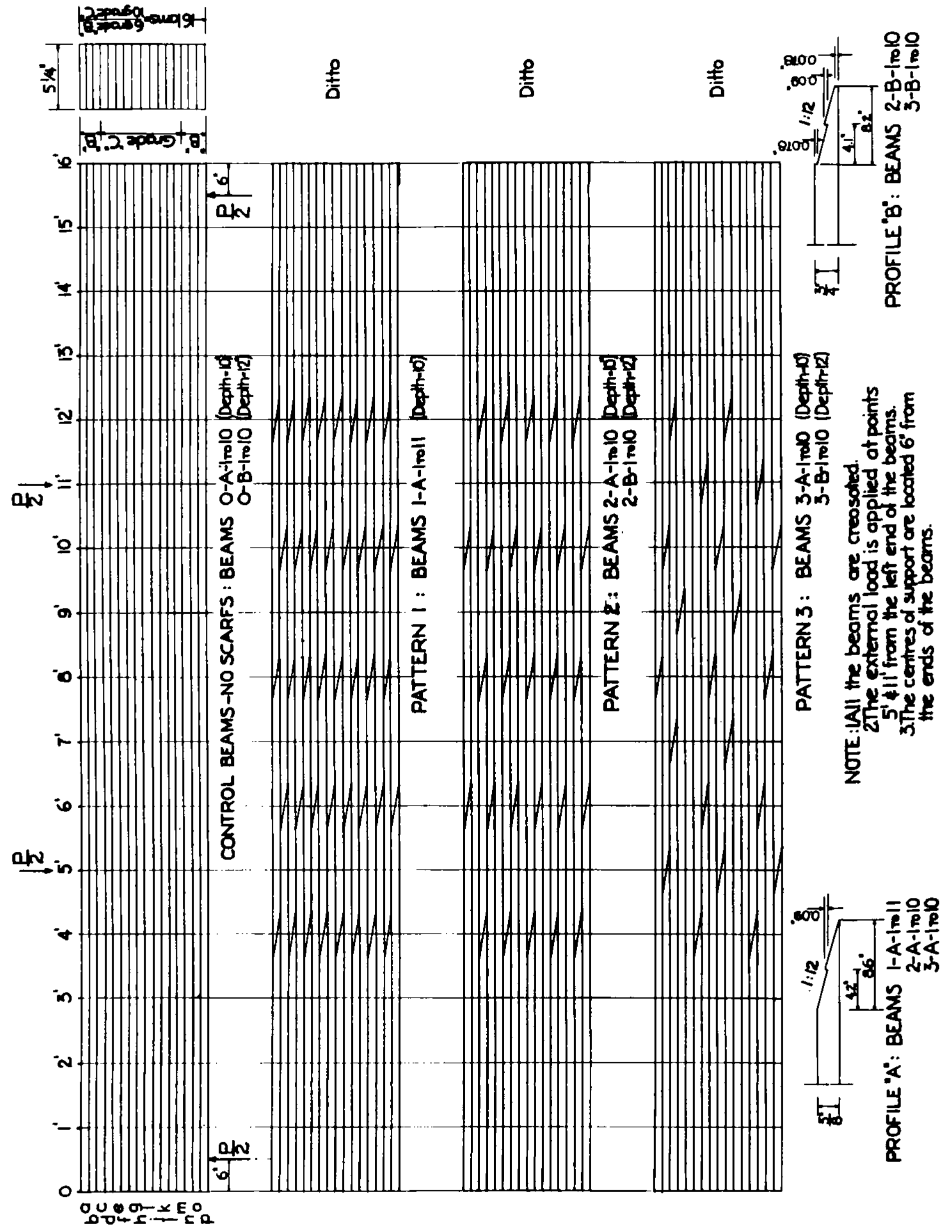

Figure 1. Layout details of test beams for effect of scarf profile and scarf pattern.

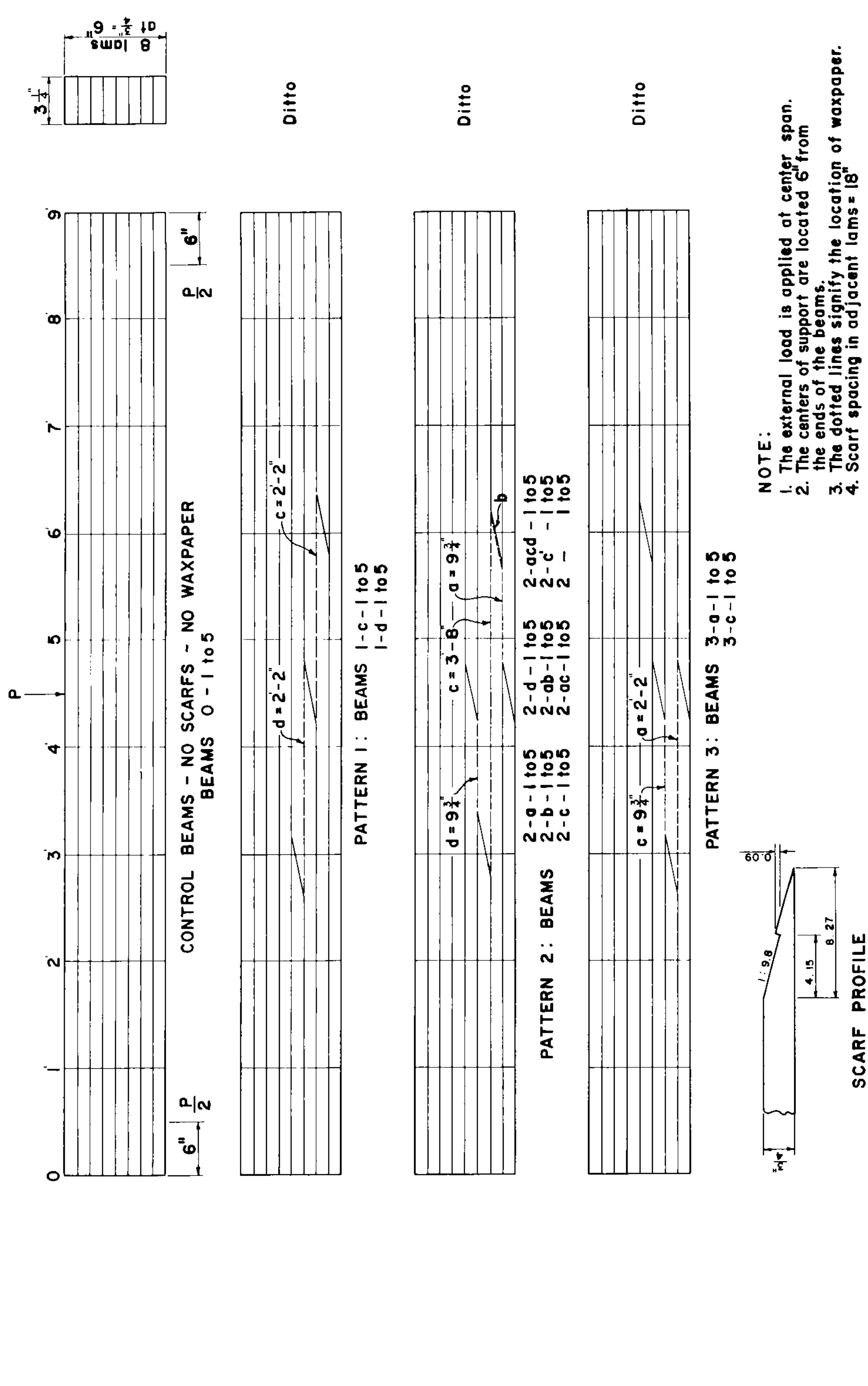

Figure 2. Layout details of test beams with built-in delamination.

indicate the location of waxpaper extending through the full width of the beam from toe to heel or vice versa of adjacent scarfs; c′ indicates that the waxpaper extends through half the width of the beam corresponding to location c; b indicates waxpaper in the scarf joint; and ab, ac, and acd indicate the placing of waxpaper at two and three locations, respectively, in the same beam, depicted by the individual letters.

The groups of beams tested are shown in Figure 2. The spacing of scarfs in adjacent laminations is 18 in.

The testing of the 70 beams was undertaken to serve as an introduction to the investigation of the effects of delamination on the strength of laminated beams subjected to flexural and accompanying shearing stresses. Previous work (*6*) has led to the derivation of a formula commonly employed in calculating longitudinal shear in checked wooden beams. The formula in question, however, assumes that checking occurs symmetrically with respect to the vertical centerline of a cross-section, the checks being contained in a plane more or less perpendicular to the vertical centerline. Further, the derivation is based on the assumption that checking occurs at mid-height of a beam, the checks being characterized by constant depth throughout the full length of the member. This, for example, does not permit a quantitative analysis of conditions of delamination extending locally through the full width of a beam, and/or delamination, and/or checking occurring at locations other than the neutral plane. It is felt that such information may prove valuable in estimating the true strength of members containing delamination.

The material employed for building these test specimens was selected from "Industrial Clears, Grade C and Better," classified according to the "BCLMA Standard Grading and Dressing Rules." According to the CSA—0122-1953 Specification, the lumber was classified as dense-grained.

Resorcinol-formaldehyde glue (Lauxite RF 900) was the adhesive used. The 70 test beams were not preservative treated.

MOISTURE CONTENT

The moisture content of the lumber employed in building the 151 test specimens ranged between 8 and 12 percent, as recorded by an electric resistance-type moisture meter. It was originally planned to specify a moisture range of 10 to 15 percent, but a survey of the available stock rendered this impractical. A range of 10 to 15 percent in the moisture content is desirable before gluing of lumber constituting a laminated member for exterior service.

EXPERIMENTAL PROCEDURE

The beams of the first section (81 beams) were tested in a Riehle, lever-type, testing machine of 200,000-lb capacity. An I-beam serving as a loading rail transferred the applied load to two points located symmetrically 6 ft apart with respect to the vertical centerline of the beam. The I-beam rested on knife-edges separated by bearing plates from the top of the beam. The contact areas between the knife-edges and the plates were oiled to minimize friction stresses introduced due to the "bridging action." The testing span for all beams was 15.0 ft, the beams being supported by plates resting on knife-edges, which in turn rested on the loading-bed of the machine. Load deflection readings were taken up to ultimate failure. The net deflection at center span was measured by an Ames dial fastened to one of the two suspended 2-in. by 4-in. by 16-ft "timbers," and in contact with a steel angle fastened to the face of the beam by means of small nails placed symmetrically about the assumed neutral axis of the member. The "timbers" were supported by two cross-arms, connected to the former by four vertical steel rods, each one of the cross-arms having two securely fastened screws resting on small plates placed on the top of the beam, directly over one of the knife-edges supporting the beam. The method employed excluded the effect on the deflection due to the crushing of fibers at the supports and loading points. The

adequacy of this method was checked prior to application.

The moisture content at failure was measured by an electric resistance-type moisture meter, unaffected by the presence of creosote. The loading rate employed was 0.15 in. per min.

Four of the 81 beams were set aside for purposes of a crude wetting-and-drying test. The beams were left outside during the period June 1957 to March 1958 and were subjected to the punishment of the weather. In March 1958 the beams were moved inside and subjected to regular wetting-and-drying cycles (uncontrolled humidity conditions prevailed). Drying heat was applied for three days followed by wetting periods of four days. The wetting-and-drying test was discontinued in the middle of July 1958. It was the purpose to observe whether checking along the glue-line, close to the glue-line, or away from the glue-line, would result, and ultimately to test these beams in bending as previously described.

The beams of the second section (70 beams) were tested in a Riehle testing machine of 60,000-lb capacity, and were loaded at center span. The method employed for measuring the net deflection at center span was similar in principle to that previously described.

An electric-type moisture meter was used to establish the moisture content of the test specimens at failure.

The rate of loading employed was 0.1 in. per min.

TEST RESULTS

The test results pertaining to the 81 beams of the first section are presented in Tables 1-9 inclusive. Figure 3 gives the load-deflection relationship for beams 0-B-1 to 10 at center span and can be considered representative for the 81 test beams, except that the load-deflection curves of the beams built up of ⅝-in. laminations are somewhat flatter. Figures 4 and 5 are representative photographs illustrating some of the various modes of failure. Fig. 6 shows the penetration of creosote in beam 0-A-5. The beam is cut into 1-ft sections to illustrate the variation in penetration of creosote along its length.

The test results may be interpreted intelligently if the following is noted:

1. To calculate extreme fiber stresses or the moduli of rupture:

$$f = \frac{M\, y_{max}}{I_g}$$

in which

f = extreme fiber stress;
M = bending moment;
y_{max} = distance from the neutral axis to the extreme fiber; and
I_g = gross moment of inertia of the cross-section.

TABLE 1

TOTAL LOAD AND DEFLECTION AT ULTIMATE FAILURE

Beam Mark	Total Load (lb)	Defl. (in.)	Beam Mark	Total Load (lb)	Defl. (in.)	Beam Mark	Total Load (lb)	Defl. (in.)	Beam Mark	Total Load (lb)	Defl. (in.)
0-A-1	31,000	3.02	1-A-1	25,600	2.53	2-A-1	25,200	2.32	3-A-1	21,800	2.17
0-A-2	30,700	3.05	1-A-2	21,900	2.32	2-A-2	22,000	2.06	3-A-2	24,800	2.63
0-A-3	29,000	2.59	1-A-3	18,000	1.99	2-A-3	21,000	1.98	3-A-3	26,000	2.46
0-A-4	27,000	2.50	1-A-4	18,300	2.12	2-A-4	25,400	2.55	3-A-4	24,200	2.39
0-A-5	31,200	2,84	1-A-5	22,000	2.07	2-A-5	26,000	2.56	3-A-5	20,000	2.06
0-A-6	27,500	2.51	1-A-6	23,700	2.21	2-A-6	22,000	2.19	3-A-6	24,800	2.55
0-A-7	30,000	2.96	1-A-7	20,600	2.11	2-A-7	26,600	2.76	3-A-7	24,000	2.59
0-A-8	28,600	2.93	1-A-8	26,000	2.65	2-A-8	19,900	1.95	3-A-8	22,000	2.31
0-A-9	30,000	2.94	1-A-9	26,000	2.67	2-A-9	23,000	2.51	3-A-9	22,300	2.47
0-A-10	29,000	2.77	1-A-10	21,400	2.20	2-A-10	19,600	1.77	3-A-10	22,400	2.31
			1-A-11	24,000	2.51						
0-B-1	43,000	2.21	2-B-1	29,300	1.67	3-B-1	33,000	1.85	B-1	27,200	1.74
0-B-2	36,000	2.02	2-B-2	28,100	1.50	3-B-2	29,400	1.61	B-2	46,000	2.98
0-B-3	41,000	2.20	2-B-3	32,200	1.89	3-B-3	28,000	1.59	B-3	39,800	2.70
0-B-4	34,500	1.98	2-B-4	30,000	1.60	3-B-4	29,500	1.70	B-4	39,000	2.31
0-B-5	45,000	2.36	2-B-5	29,500	1.89	3-B-5	27,000	1.61	B-5	28,000	1.70
0-B-6	44,000	2.64	2-B-6	34,200	1.89	3-B-6	30,000	1.81	B-6	26,000	1.51
0-B-7	40,000	2.09	2-B-7	23,800	1.32	3-B-7	28,000	1.75	B-7	37,300	2.17
0-B-8	40,000	2.20	2-B-8	30,000	1.82	3-B-8	31,400	1.86	B-8	35,400	2.11
0-B-9	48,000	2.59	2-B-9	28,000	1.48	3-B-9	29,400	1.77	B-9	34,800	2.42
0-B-10	40,000	2.18	2-B-10	27,300	1.61	3-B-10	29,300	1.76	B-10	40,000	2.42

TABLE 2

PHYSICAL PROPERTIES OF TEST BEAMS [1]

Beam Mark	Width (in.)	Depth (in.)	Area (in.^{2})	Sect. Mod., S (in.^{3})	Mom. Inert., I (in.^{4})	Proport. Limit (psi) Flex. Stress	Proport. Limit (psi) Corr. Shear Stress	Proport. Limit (psi) $E \times 10^{-3}$	Stress at Init. Fail. (psi) Flex. Stress	Stress at Init. Fail. (psi) Corr. Shear Stress	Modulus of Rupture (psi) Flex. Stress	Modulus of Rupture (psi) Corr. Shear Stress	Primary Modes of Failure [2]
0-A-1	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	7065	331	2266	—	—	9147	429	CGT
0-A-2	$5\frac{5}{16}$	10	53.13	88.54	442.70	7232	335	2302	8462	392	9286	430	CGT
0-A-3 [3]	$5\frac{3}{8}$	$10\frac{1}{4}$	55.09	94.11	482.31	7388	351	2220	—	—	8248	391	CGT
0-A-4 [3]	$5\frac{3}{8}$	$10\frac{1}{8}$	54.42	91.83	464.89	6983	327	2263	—	—	7865	369	CGT
0-A-5	$5\frac{5}{16}$	10	53.13	88.54	442.70	7547	349	2418	—	—	9438	437	CGT
0-A-6	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	7148	335	2325	—	—	8201	384	HS
0-A-7	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	7148	335	2254	—	—	8954	420	CGT
0-A-8	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	7065	331	2161	7659	359	8433	395	CGT + HS
0-A-9	$5\frac{3}{8}$	$10\frac{1}{8}$	54.42	91.83	464.89	6983	327	2202	—	—	8747	410	CGT
0-A-10	$5\frac{5}{16}$	10	53.13	88.54	442.70	7852	364	2358	7852	364	8767	406	CGT
1-A-1	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	6628	309	2172	—	—	7725	360	ST + SPT
1-A-2	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	6516	305	1931	—	—	6516	305	ST
1-A-3	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	4740	222	1880	—	—	5342	250	ST
1-A-4	$5\frac{5}{16}$	$10\frac{1}{16}$	53.46	89.66	451.11	4743	221	1860	—	—	5436	253	Sim T
1-A-5	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	6546	307	2171	—	—	6546	307	CGT
1-A-6	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	7146	333	2236	—	—	7146	333	ST
1-A-7	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	5342	250	2035	—	—	6125	287	CGT
1-A-8	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	6245	293	2145	—	—	7750	363	ST + CGT
1-A-9	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	6470	303	2070	7213	338	7659	359	CGT
1-A-10	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	6019	280	2079	—	—	6445	300	ST + CGT
1-A-11	$5\frac{5}{16}$	10	53.13	88.54	442.70	6023	279	2129	—	—	7242	335	CGT
2-A-1	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	6470	303	2260	—	—	7422	348	ST
2-A-2	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	5409	252	2252	—	—	6628	309	CGT
2-A-3	$5\frac{3}{16}$	$10\frac{1}{8}$	52.52	88.63	448.69	6321	296	2186	—	—	6321	296	CGT
2-A-4	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	5280	247	2115	—	—	7481	351	CGT
2-A-5	$5\frac{5}{16}$	$10\frac{3}{16}$	54.12	91.89	468.07	6626	313	2217	6626	313	7566	357	ST
2-A-6	$5\frac{3}{16}$	10	51.88	86.46	432.30	6168	286	2162	—	—	6792	314	ST
2-A-7	$5\frac{1}{8}$	$10\frac{1}{8}$	51.89	87.56	443.27	4240	199	2081	—	—	8125	381	ST + SPT
2-A-8	$5\frac{3}{16}$	$10\frac{1}{16}$	52.20	87.54	440.44	6061	282	2144	—	—	6061	282	CGT
2-A-9	$5\frac{3}{16}$	$10\frac{1}{16}$	52.20	87.54	440.44	6708	313	1960	—	—	7017	327	Sim T
2-A-10	$5\frac{3}{16}$	$10\frac{1}{16}$	52.20	87.54	440.44	5968	278	2315	—	—	5968	278	CGT
3-A-1	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	5875	275	2062	—	—	6410	300	ST + Sim T
3-A-2	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	6628	309	2021	6628	309	7481	349	CGT
3-A-3	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	6546	307	2207	—	—	7750	363	ST + Sim T
3-A-4	$5\frac{3}{8}$	$10\frac{1}{8}$	54.42	91.83	464.89	5807	272	2043	—	—	7042	330	CGT
3-A-5	$5\frac{5}{16}$	$10\frac{1}{8}$	53.79	90.77	459.52	3495	164	2111	—	—	5875	275	CGT
3-A-6	$5\frac{5}{16}$	$9\frac{15}{16}$	52.79	87.43	434.42	4864	224	2127	6717	309	7489	345	CGT
3-A-7	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	6019	280	1960	—	—	7238	337	Sim T
3-A-8	$5\frac{1}{8}$	$10\frac{1}{16}$	51.57	86.49	435.16	4292	200	2153	—	—	6790	316	CGT
3-A-9	$5\frac{1}{4}$	$10\frac{1}{16}$	52.83	88.60	445.77	4800	224	2024	4983	232	6720	313	CGT
3-A-10	$5\frac{1}{4}$	$10\frac{1}{8}$	53.16	89.71	454.16	4740	222	2091	—	—	6967	327	HS

TABLE 2—*Continued*

Beam Mark	Width (in.)	Depth (in.)	Area (in.^{2})	Sect. Mod., S (in.^{3})	Mom. Inert., I (in.^{4})	Proport. Limit (psi) Flex. Stress	Proport. Limit (psi) Corr. Shear Stress	Proport. Limit (psi) $E \times 10^{-3}$	Stress at Init. Fail. (psi) Flex. Stress	Stress at Init. Fail. (psi) Corr. Shear Stress	Modulus of Rupture (psi) Flex. Stress	Modulus of Rupture (psi) Corr. Shear Stress	Primary Modes of Failure [2]
0-B-1	5 1/4	12	63.00	126.00	756.00	8475	471	2607	8475	471	9161	509	CGT
0-B-2 [3]	5 3/8	12 1/4	65.84	134.42	823.32	5172	293	2288	—	—	7181	407	CGT
0-B-3	5 1/4	12	63.00	126.00	756.00	6375	354	2448	7232	402	8732	485	SPT
0-B-4 [3]	5 3/8	12 1/4	65.84	134.42	823.32	5172	293	2154	—	—	6880	390	CGT
0-B-5	5 5/16	12 1/8	64.41	130.16	789.10	8660	486	2509	8660	486	9283	521	CGT
0-B-6	5 3/8	12 1/4	65.84	134.42	823.32	5976	339	2190	8386	476	8788	498	CGT
0-B-7	5 5/16	12 3/16	64.75	131.52	801.46	8160	460	2249	—	—	8160	460	CGT
0-B-8	5 1/4	12 1/8	63.66	128.65	779.94	7083	398	2289	—	—	8342	468	CGT
0-B-9	5 1/4	12 1/4	64.31	131.30	804.21	8174	464	2247	—	—	9819	557	CGT + Sim T
0-B-10	5 1/4	12	63.00	126.00	756.00	8518	473	2285	—	—	8518	473	CGT
2-B-1	5 5/16	12 3/16	64.75	131.52	801.46	5964	336	2054	—	—	5964	336	CGT
2-B-2	5 3/8	12 3/16	65.51	133.07	810.90	5225	295	2237	5610	317	5651	319	ST
2-B-3	5 1/4	12 1/8	63.66	128.65	779.94	6286	353	2110	6286	353	6705	376	ST
2-B-4	5 1/4	12 3/16	63.98	129.96	791.95	6181	349	2211	—	—	6181	349	ST
2-B-5	5 3/8	12 3/16	65.51	133.07	810.90	5042	284	2017	5042	284	5935	335	ST
2-B-6	5 1/4	12 1/16	63.33	128.65	779.94	6663	376	2190	—	—	7125	402	ST
2-B-7	5 5/16	12 3/16	64.75	131.52	801.46	4835	273	2084	—	—	5697	321	ST
2-B-8	5 5/16	12 1/8	64.41	130.16	789.10	5756	323	1989	—	—	6171	346	ST
2-B-9	5 1/4	12 1/4	64.31	131.30	804.21	5295	300	2213	—	—	5706	324	CGT
2-B-10	5 3/16	12 1/8	62.90	127.11	770.60	5045	283	2156	5045	283	5895	331	CGT
3-B-1	5 1/4	12 1/4	64.31	131.30	804.21	4884	277	2216	—	—	6735	382	ST
3-B-2	5 3/8	12 3/16	65.51	133.07	810.90	5225	295	2120	—	—	5915	334	ST
3-B-3	5 5/16	12 1/4	65.08	132.87	813.83	4826	274	2090	—	—	5639	320	CGT
3-B-4	5 5/16	12 1/4	65.08	132.87	813.83	4420	251	2002	—	—	5944	337	ST
3-B-5	5 5/16	12 1/4	65.08	132.87	813.83	5233	297	1964	5233	297	5436	308	ST
3-B-6	5 3/8	12 3/16	65.51	133.07	810.90	5630	318	1935	—	—	6036	341	CGT
3-B-7	5 3/8	12 1/8	65.17	131.70	798.43	5689	319	1870	—	—	5689	319	ST
3-B-8	5 1/8	12 1/4	62.78	128.18	785.10	5424	308	2086	5424	308	6561	372	CGT
3-B-9	5 3/8	12 1/4	65.84	134.42	823.32	5855	332	1976	—	—	5856	332	ST
3-B-10	5 3/8	12 5/16	66.18	135.81	836.09	5775	329	1861	—	—	5775	329	ST
B-1	5 3/8	12 1/8	65.17	131.70	810.90	5279	296	1863	5279	296	5525	310	CGT
B-2	5 1/4	12 1/8	63.66	128.65	779.94	5404	303	2035	—	—	9602	539	Sim T
B-3	5 3/8	12 3/16	65.51	133.07	810.90	6848	386	1818	—	—	8025	453	CGT
B-4	5 5/16	12 1/4	65.08	132.87	813.83	3607	205	2123	7671	435	7874	447	CGT
B-5	5 3/8	12 1/8	65.17	131.70	798.43	4459	250	1953	—	—	5689	319	CGT + Sim T
B-6	5 3/8	12 1/8	65.17	131.70	798.43	5279	296	2014	—	—	5279	296	CGT
B-7	5 3/8	12 3/16	65.51	133.07	810.90	6442	363	2100	7254	409	3341 [4] 7517 [5]	424	CGT + HS
B-8	5 3/16	12 1/8	62.90	127.11	770.60	4620	259	2070	—	—	3318 [4] 7466 [5]	419	HS + ST
B-9	5 5/16	12 1/8	64.41	130.16	789.42	4097	230	1999	5342	300	7167	402	CGT
B-10	5 3/16	12 3/16	63.22	128.42	782.57	6675	377	2037	—	—	8357	472	HS

[1] Moisture content of test beams 9 to 12 percent (average 10 percent). All stress calculations based on gross moment of inertia.
[2] CGT = cross-grain tension; Sim T = simple tension; HS = horizontal shear; ST = scarf tension; SPT = splintering tension.
[3] Subjected to wetting-and-drying cycles.
[4] At presumed section of failure.
[5] At center 6 ft of beam at failure.

TABLE 3

MEAN ULTIMATE FAILURE STRESS (MODULUS OF RUPTURE)

Beam Mark	Scarf Failures				Other Failures				Scarf + Other Failures			
	n	$\bar{x}$	s	V	No.	$\bar{x}$	s	V	No.	$\bar{x}$	s	V
0-A-1 to 10 [a]	—	—	—	—	7	8967	349	3.9	7	8967	349	3.9
0-B-1 to 10 [b]	—	—	—	—	8	8850	546	6.2	8	8850	546	6.2
0-A-1 to 10 [a] / 0-B-1 to 10 [b]	—	—	—	—	15	8905	452	5.1	15	8905	452	5.1
1-A-1 to 11	6	6821	917	13.4	5	6602	883	13.4	11	6721	864	12.8
2-A-1 to 10	4	7476	548	7.3	6	6579	586	8.9	10	6938	711	10.2
3-A-1 to 10 [c]	2	7080	942	13.3	7	6909	970	14.0	9	6977	594	8.5
2-B-1 to 10	7	6209	538	8.7	3	5855	134	2.3	10	6103	476	7.8
3-B-1 to 10	7	5907	403	6.8	3	6079	462	7.6	10	5959	404	6.8
B-1 to 10	—	—	—	—	10	7250	1381	19.1	10	7250	1381	19.1

[a] Beams 0-A-3, 0-A-4, and 0-A-6 not included.
[b] Beams 0-B-2 and 0-B-4 not included.
[c] Beam 3-A-10 not included.

TABLE 4

DATA ON WETTING AND DRYING CYCLES[a]

Beam Mark	Avg. Room Temp. (°F)	Avg. Surf. Temp. of Beam[b] (°F)		Checks (in.)[c]		
		When Heating	When Wetting	Length	Depth	Max. Depth
0-A-3 [d]	70	180	60	36	3/8	1/2
0-A-4 [d]	70	180	60	—	—	—
0-B-2 [e]	70	180	60	60	1/8	1/4
0-B-4 [e]	70	180	60	48	1/8	1/2

[a] Uncontrolled humidity conditions; total duration of cycles, 119 days.
[b] Center 3 ft.
[c] Checks occurred close to glue line.
[d] $\bar{x} = 8057$ psi at failure.
[e] $\bar{x} = 7030$ psi at failure.

TABLE 6

ESTIMATE OF LOWER EXCLUSION LIMITS (MODULUS OF RUPTURE)

Beam Mark	Estimate				
		$\bar{x} - 1.96s$ [a]		$\bar{x} - 2.4s$ [c]	
	$\bar{x}$	Value	s [b]	Value	s [b]
0-A-1 to 10 [d] / 0-B-1 to 10 [e]	8905	7722	191	7456	206
1-A-1 to 11	6721	5538	213	5272	226
2-A-1 to 10 / 3-A-1 to 10 [f]	6957	5774	177	5508	193
2-B-1 to 10 / 3-B-1 to 10	6031	4848	174	4582	191
B-1 to 10	7250	4540	775	3935	895

[a] Value exceeded by 97½ percent of population.
[b] Standard deviation of lower exclusion limit.
[c] Value exceeded by 99 percent of population.
[d] Beams 0-A-3, 0-A-4, and 0-A-6 not included.
[e] Beams 0-B-2 and 0-B-4 not included.
[f] Beam 3-A-10 not included.

TABLE 5

STRENGTH RATIOS (MODULUS OF RUPTURE)

Beam Mark	Scarf Failures		Other Failures		Scarf + Other Failures = Total Sample				Strength Ratios[a]	
					Groups Separate		Groups Combined			
	Flex. Stress (psi)	Strength Ratio	Flex. Stress (psi)	Strength Ratio	Flex. Stress (psi)	Strength Ratio	Flex. Stress (psi)	Strength Ratio	Scarf Failures	Other Failures
0-A-1 to 10 [b] / 0-B-1 to 10 [c]	8905	1.000	8905	1.000	8905	1.000	8905	1.000	—	—
1-A-1 to 11	6821	0.766	6602	0.741	6721	0.755	6721	0.755	101.5	98.1
2-A-1 to 10	7476	0.840	6579	0.739	6938	0.779	6957	0.781	107.8	94.9
3-A-1 to 10 [d]	7080	0.795	6909	0.776	6977	0.784			101.4	99.0
2-B-1 to 10	6209	0.697	5855	0.657	6103	0.685	6031	0.677	101.8	95.9
3-B-1 to 10	5907	0.663	6079	0.683	5959	0.669			99.1	102.1

[a] Expressed as percentages of corresponding strength ratio of total sample.
[b] Beams 0-A-3, 0-A-4, and 0-A-6 not included.
[c] Beams 0-B-2 and 0-B-4 not included.
[d] Beam 3-A-10 not included.

TABLE 7

MODULUS OF RUPTURE FOR VARIOUS EXCLUSIONS

Joints			Modulus of Rupture (psi)					
			Average		2½ Percent Exclusion		1 Percent Exclusion	
Slope	Type	Pattern	Value	%	Value	%	Value	%
—	—	—	8900	100	7720	100	7450	100
12	H	2 and 3	6950	78	5770	75	5510	74
12	H	1	6720	75	5540	72	5270	71
12	HS	2 and 3	6030	68	4850	63	4580	62
10	H	Random	7250	81	4540	59	3940	53

TABLE 8

EFFECT OF KNOT DISTRIBUTION CHARACTERISTICS ON I_{net}/I_g RATIO

Beam Mark	Avg. I_{net}/I_g (%)	Est. I_{net}/I_g Exceeded by 99.5% Pop.	Std. Dev. of Est.	Est. I_{net}/I_g Exceeded by 99.5% Pop. (95% Conf.)
0-A-1 to 5 0-B-1 to 5	95.5	86.8	1.24	84.3

TABLE 9

COMPARISON OF CSA 0122-1953 DESIGN STRESSES WITH TEST RESULTS

Beam Mark	Test Results				CSA (Close-Grained Douglas Fir, Dry Service Conditions, Long-Term Loading)			
	Est. Mod. of Rupture Exceeded by 97½% of Pop. (psi)		Long-Term Load Design Stress (psi)		% to Be Applied to Basic Stress with Knot Distribution control, CSA-0122-1953 Clause 82	Resulting Design Stress (psi)	% to Be Applied to Basic Stress with Normal Grad.	Resulting Design Stress (psi)
	Test Cond.	Long Term Loading[a]	F.S.= 1.67	F.S.= 1.5				
0-A-1 to 10[b] 0-B-1 to 10[c]	7722	4344	2600	2895	90	2646	71.4	2100
1-A-1 to 11	5538	3115	1870	2075	79	2322	71.4	2100
2-A-1 to 10 3-A-1 to 10[d]	5774	3248	1950	2165	78 81	2313 2381	71.4	2100
2-B-1 to 10 3-B-1 to 10	4848	2727	1630	1820	79 80	2322 2352	71.4	2100
B-1 to 10	4540	2550	1530	1710	—	—	—	—

[a] Traditional long-term loading factor of 9/16 applied to test results.
[b] Beams 0-A-3, 0-A-4, and 0-A-6 omitted.
[c] Beams 0-B-2 and 0-B-4 omitted.
[d] Beam 3-A-10 omitted.

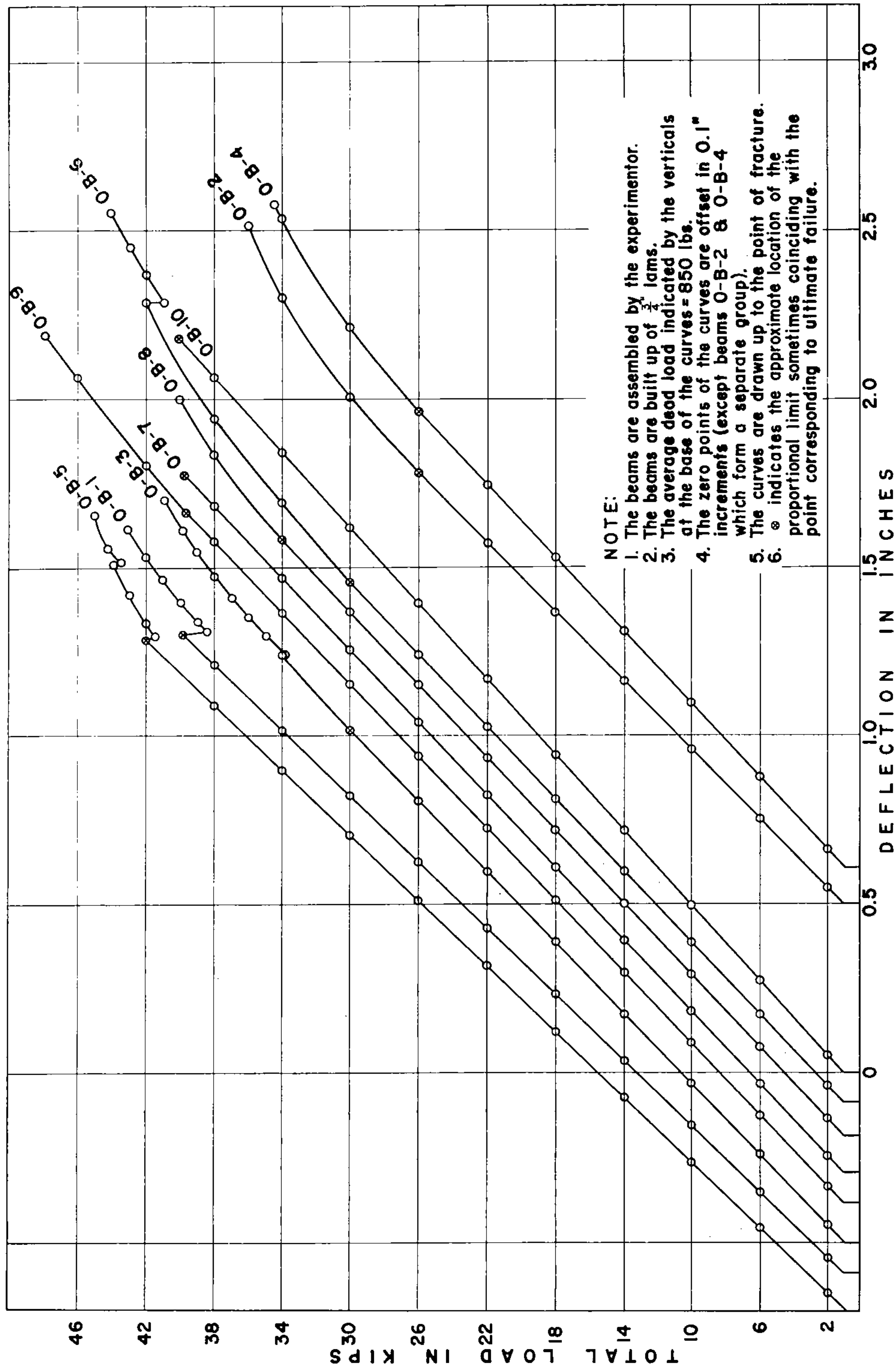

Figure 3. Load-deflection curves for beams 0-B-1 to 10.

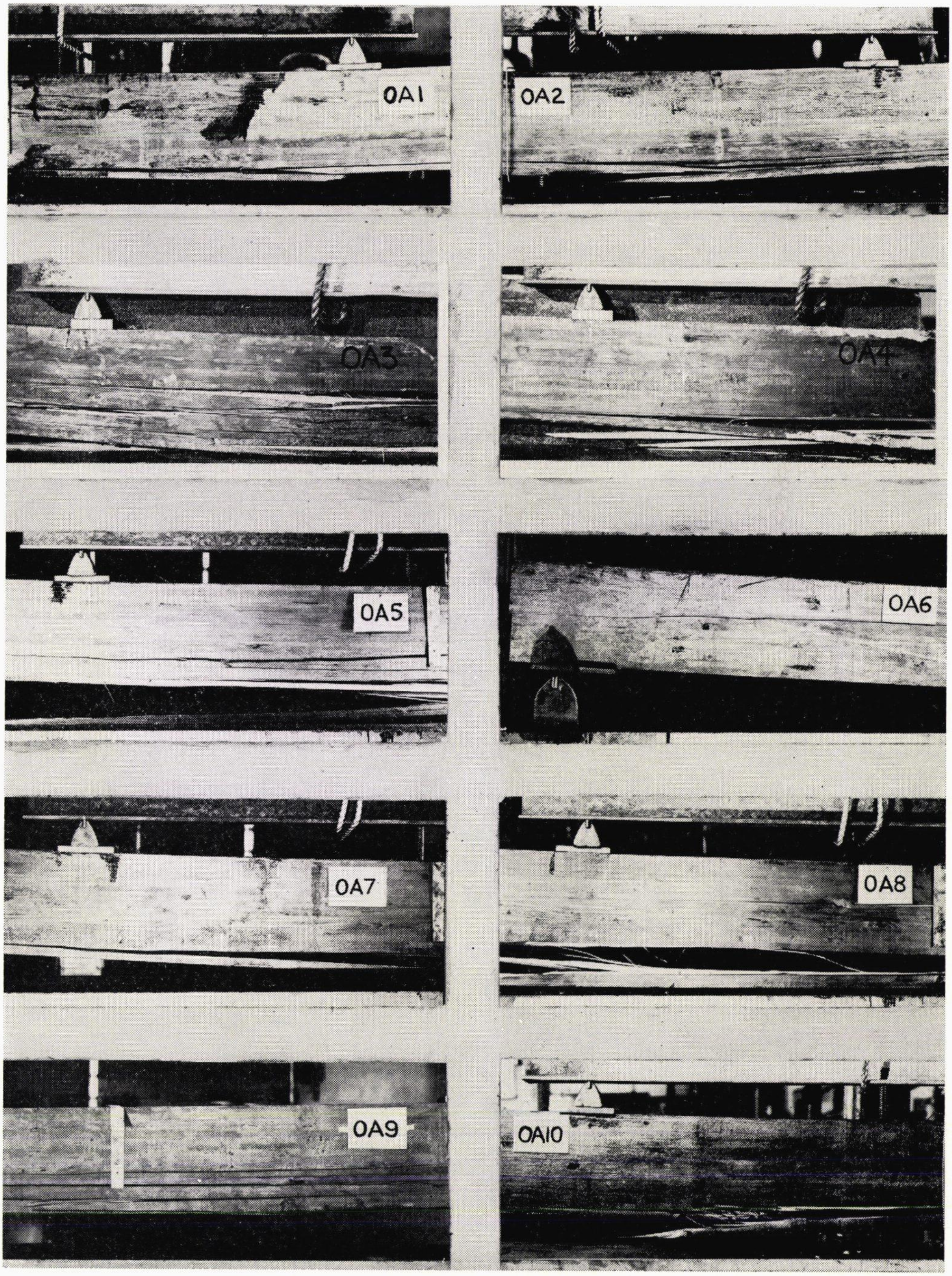

Figure 4. Representative modes of failure.

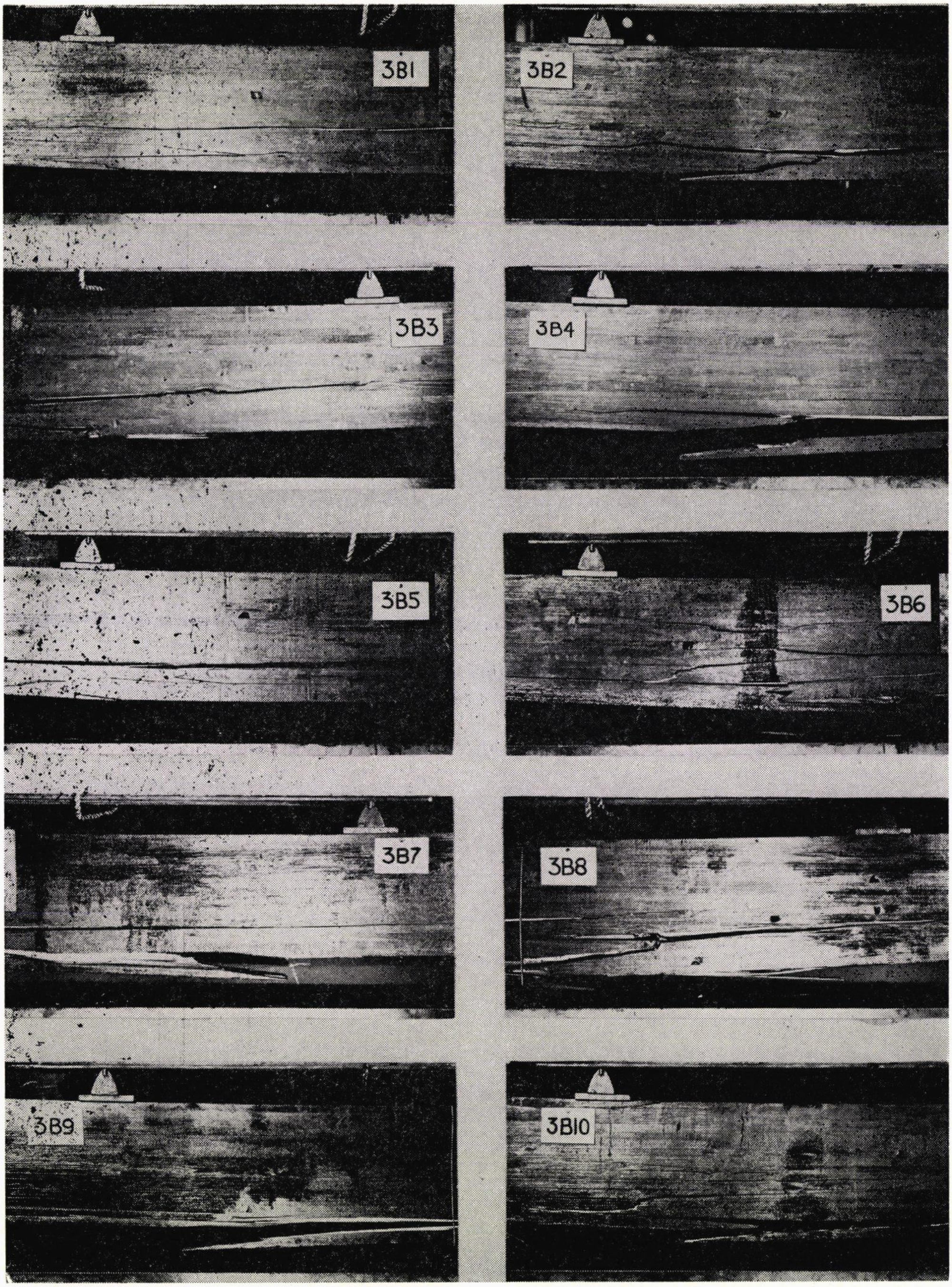

Figure 5. Representative modes of failure.

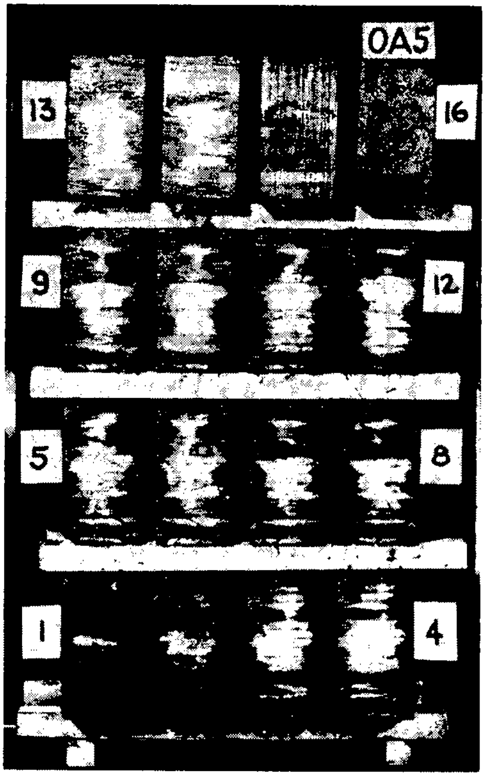

Figure 6. Example of creosote penetration (1-ft sections along length of 16-ft beam).

2. To calculate shear:

$$v = 1.5 \frac{V}{A}$$

in which

v = shearing stress at the neutral axis;
V = shearing force; and
A = gross area of the cross-section.

3. Strength Ratio (Test Beams) =

$$\frac{\text{modulus of rupture of "jointed" beams}}{\text{modulus of rupture of "unjointed" control}}$$

4. Referring to Table 8:

$$I_{net} = I_g - I_{knot}$$

in which

I_{knot} is the moment of inertia of knots about the neutral axis of beam;

$$I_g = \frac{1}{12} b (16t)^3$$

in which

b is the width of beam;
t is the thickness of lamination; and

$$I_{knot} = \frac{1}{12} k\, t^3 + k\, t (n\, t)^2$$

in which

k is the width of knot and
n is the knot in the nth lamination from the neutral axis.

The computations of the I_{net}/I_g ratios are based on a knot survey of 160 16-ft boards. The sum of the widths of all knots within a unit of length equal to the width of the piece is considered ineffective at the cross-section.

5. Strength Ratio (CSA 0122-1953) =

$$\frac{\text{strength of clear material—strength reductions due to grade}}{\text{strength of clear material}}$$

Clear material is used as a base of reference. The strength ratio is obtained from a comparison of cross-sectional areas, perpendicular to the direction of stress, for members subjected to tension. The flexural strength of a member is measured by its moment of inertia about the neutral axis. After proper allowance due to inherent growth characteristics has been made, the effects due to end-jointing are considered. A lamination containing a plain scarf of a slope 1 in 12 or flatter has its strength reduced 10 percent as compared to an unjointed lamination. Further, the specification is interpreted to say that only one notch in a hooked scarf joint with end steps need be considered ineffective in transmitting stress. The values in Col. 6, Table 9, are based on this assumption. These values pertaining to hooked feathered scarf joints have been computed assuming the hook ineffective in transmitting stress. Stress concentrating effects are not taken into account adequately by this procedure. The notch and slope effects of scarf joints are cumulative.

Example: Beams 1-A-1 to 11

$$\frac{I_g - I_{notch}}{I_g} = 0.928$$

Slope effect = 0.9 (CSA 0122-1953)
Strength ratio to be applied to basic stress = $0.928 \times 0.9 = 0.835$, or appr. 84%
Further reduction due to a conservative estimate of the presence of knots = 5%
Net strength ratio to be applied to basic stress = $84 - 5 = 79\%$

6. The statistical analyses were based on utilization of the well-known t and F tests. The lower exclusion limits are based on an assumed normal distribution. The statistical analyses performed were supervised by Dr. D. A. S. Fraser, Department of Mathematics, University of Toronto. The analyses are described in detail elsewhere (*1*).

Referring to Tables 3, 4, and 6:

n = number of specimens within each group;
$\bar{x}$ = measured sample average;
s = standard deviation; and
$V = \frac{100s}{\bar{x}}$ = coefficient of variation.

The test results pertaining to the 70 beams of the second section are presented in Table 10 and Fig. 7. The bar diagram (Fig. 7) is drawn up with respect to the total load applied and does not differentiate between the various modes of failure.

TABLE 10
CHARACTERISTICS OF THE ARTIFICIALLY DELAMINATED TEST BEAMS AT FAILURE

Beam Mark	Adjusted Max. Load (lb)[a]	Primary Modes of Failure[b]	Beam Mark	Adjusted Max. Load (lb)[a]	Primary Modes of Failure[b]
0-1	8,650	CGT	2-1	8,216	CGT
0-2	7,780	SPT	2-2	7,392	ST
0-3	7,360	CGT	2-3	8,990	ST
0-4	8,900	SPT	2-4	8,333	ST
0-5	9,964	CGT	2-5	9,325	ST
2-acd-1	5,972	Sim T	2-ab-1	6,624	ST
2-acd-2	6,100	HS	2-ab-2	7,930	ST
2-acd-3	6,206	HS	2-ab-3	6,140	CGT
2-acd-4	6,389	HS	2-ab-4	7,576	Sim T
2-acd-5	6,990	HS	2-ab-5	7,776	ST
2-c-1	5,635	HS	3-a-1	7,812	CGT
2-c-2	7,078	HS	3-a-2	8,003	HS
2-c-3	6,185	HS	3-a-3	7,894	CGT
2-c-4	7,091	HS	3-a-4	8,700	HS
2-c-5	7,354	HS	3-a-5	8,159	HS
2-ac-1	6,447	HS	1-c-1	6,320	ST
2-ac-2	5,883	HS	1-c-2	7,097	ST
2-ac-3	6,918	HS	1-c-3	6,430	HS
2-ac-4	5,704	HS	1-c-4	6,208	HS
2-ac-5	6,100	HS	1-c-5	6,824	HS
2-a-1	8,813	CGT	2-d-1	7,638	HS
2-a-2	8,093	HS	2-d-2	7,411	HS
2-a-3	8,226	HS	2-d-3	7,271	HS
2-a-4	8,370	ST	2-d-4	7,219	HS
2-a-5	8,098	HS	2-d-5	7,360	CGT
2-b-1	8,427	ST	2-c'-1	7,877	CGT
2-b-2	9,288	ST	2-c'-2	7,668	CGT
2-b-3	6,624	ST	2-c'-3	7,829	ST
2-b-4	6,500	CGT + HS	2-c'-4	8,371	Sim T
2-b-5	7,038	CGT	2-c'-5	7,407	ST
3-c-1	6,773	CGT	1-d-1	6,721	HS
3-c-2	6,600	ST	1-d-2	5,500	HS
3-c-3	6,956	HS	1-d-3	6,092	HS
3-c-4	7,406	CGT	1-d-4	5,750	HS
3-c-5	8,206	HS	1-d-5	5,820	HS

[a] M.C. = 12 percent.
[b] See Table 2 for meaning of symbols.

DISCUSSION

Specific gravity and shear tests were not undertaken. Examination of the failures confirmed the adequacy of the glue bond. The four beams (0-A-3, 0-A-4, 0-B-2, and 0-B-4) subjected to the weathering cycles revealed a minimum of delamination.

Moisture content readings taken close to the location of failure ranged between 9 and 12 percent (based on oven dry weight) with an estimated average of 10 percent for the 81 test beams of the first section. The corresponding value for the 70 beams of the second section was 10.5 percent. Values are not given for the moisture content of each individual beam.

LOCATION AND PRIMARY MODE OF FAILURE

The failures were classified according to the appearance of the fractured surface. The system employed (ASTM-D143-52) classifies failures occurring in static bending tests into six major groups (Fig. 8) as follows:

1. Simple tension.
2. Cross-grain tension.
3. Splintering tension.
4. Brash tension.
5. Compression.
6. Horizontal shear.

One additional designation, "scarf tension," was introduced to describe the occurring modes of failure. This designation describes a failure occurring in a scarf joint located in the extreme tension

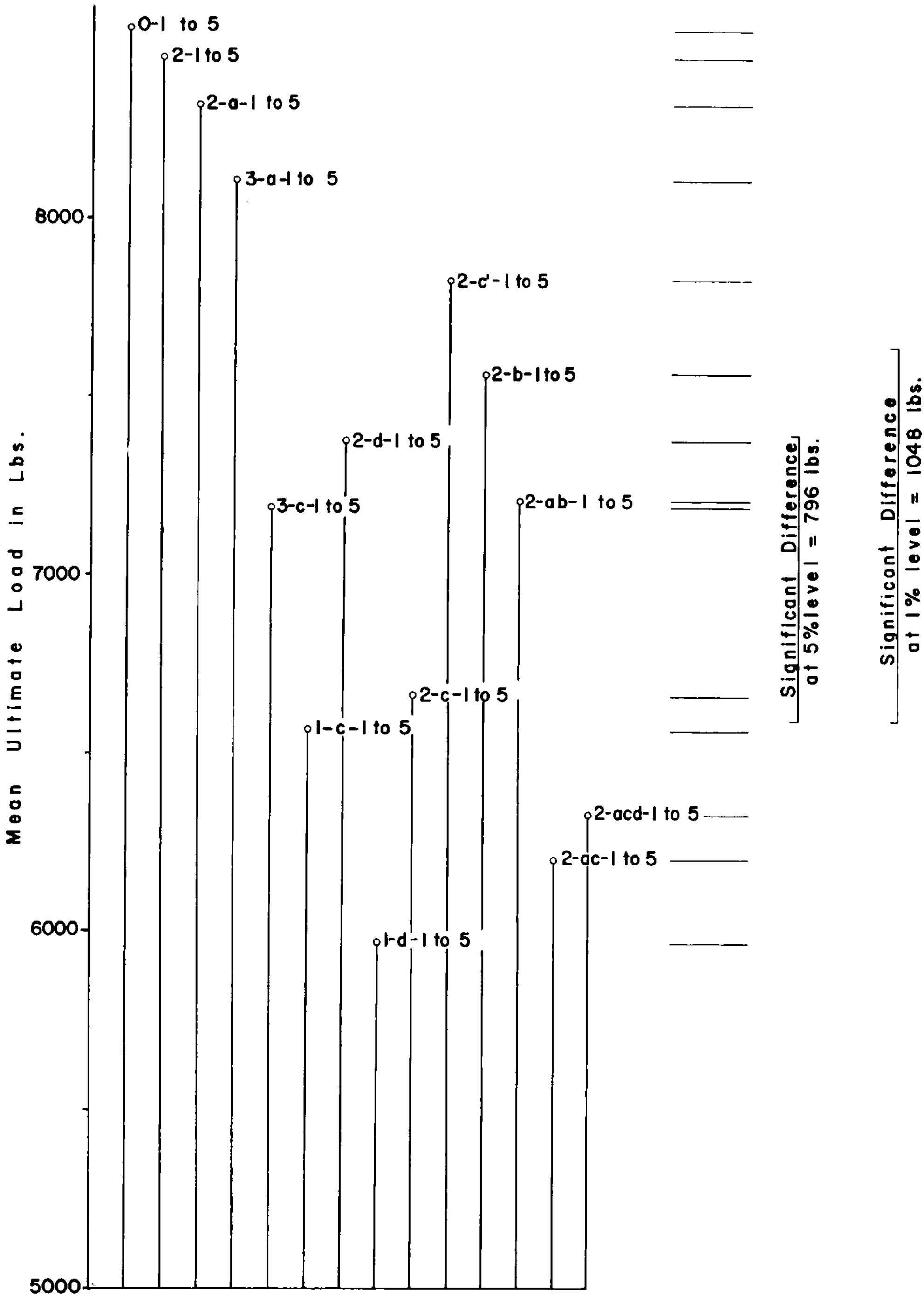

Figure 7. Test of significant differences on beams with built-in delamination.

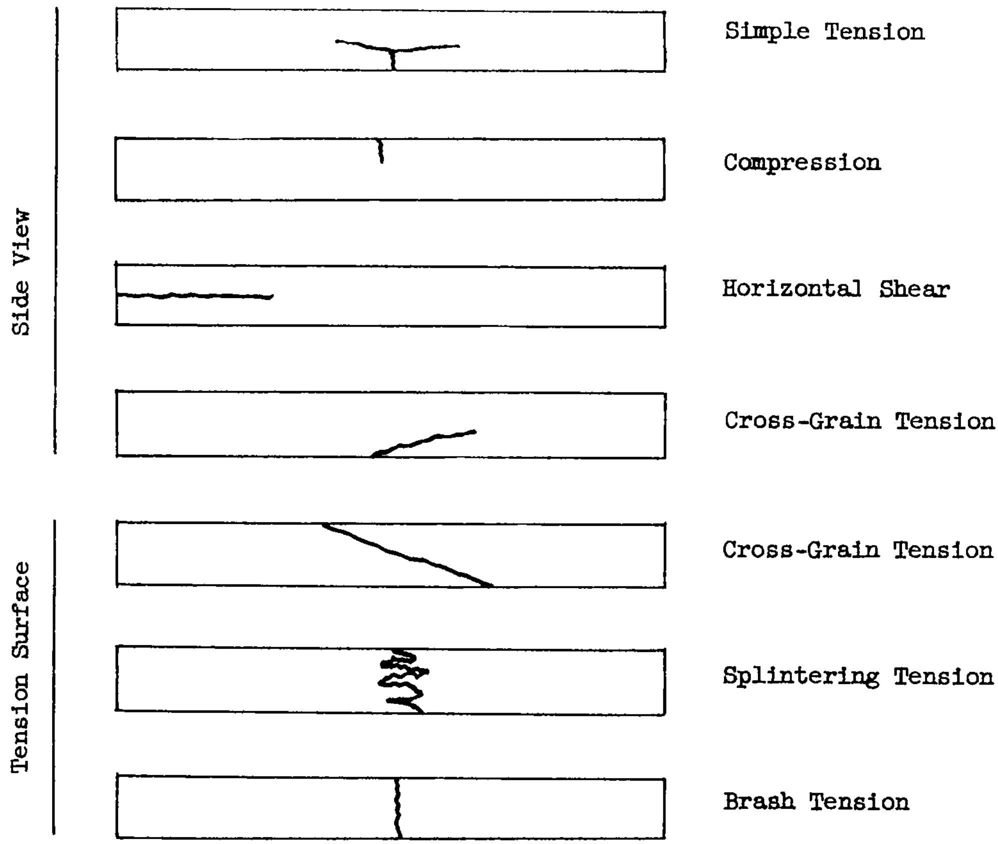

Figure 8. Types of failures in static bending (ASTM-D143-52).

lamination of a beam, the failure line progressing more or less parallel to the glue line of the joint. Beam 3-B-10 (Fig. 5) illustrates this condition clearly.

The seven types of failures quoted cannot definitely describe the large variety of failures possible in a non-homogeneous material such as wood. In laminated timber members the location of failure lines in relation to the glue line is of importance. Fox (*2*) discusses "deep" and "shallow" wood failures. Attention is, however, drawn to the fact that shallow wood failures associated with high failure loads are an indication of a good joint. For example, certain types of glue (such as polyvinyl resin emulsions and latex-based casein glues) seldom show a high percentage wood failure. This is particularly so when they are used with smooth-surfaced high-density wood species. Consequently, percentage wood failure alone is not a reliable means of assessing the quality of a glue joint, but must be considered in conjunction with the load at failure.

The test results disclosed several types of failure. Variations of cross-grain failure were particularly abundant. Simple and splintering tension, including a few shear failures, could be observed. No brash tension or compression failures seemed to be present. In Table 2 the various types of failures are briefly classified under "Primary Modes of Failure." Attention is directed towards the adjective "Primary." Due to bleeding and the surfaces of the beams being covered with creosote, it was extremely difficult to locate the origin of failure. This was

particularly true where the beam failed in stages. Flexural stresses corresponding to the first abrupt drop in load, at more or less constant deflection, are summarized under "Stress at Initial Failure" in Table 2. In several instances it was impossible to detect the "resulting crack." It is possible that these "failures" were due to localized strains in the outside tension lamination or deformations within the beam. In any case, it was impossible to establish this from visual inspection.

In instances where the resulting cracks could be observed, these always occurred at locations of local deviation in grain, such as knots in the bottom lamination. Careful observation seemed to disclose that these cracks were of a very localized nature and did not extend through the full width of the lamination. Therefore, it could not be safely stated that the bottom lamination had failed. In some instances ultimate failure resulted from an "enlargement" of the initial failure, in others the ultimate failure seemed to have originated altogether at another location. Based on the described observations it was concluded that the true strength of the beam is measured by the stress at ultimate failure and not by the stress at "initial failure" or other intermediate stages.

The final or ultimate failure resulted in a complete breakdown of the beam. As previously mentioned, cross-grain failures were abundant. Failures seemingly starting off due to deviations in grain at or close to knot-holes in the bottom lamination were sometimes classified as cross-grain tension, simple tension, or a combination of both. The latter classification does not strictly adhere to the clearly outlined ASTM-classification of the modes of failure, but rather utilizes this classification to formulate a descriptive picture. Other combinations are described in Table 2.

The relative frequency of cross-grain failures was an unexpected phenomenon. Cross-grain failures can be divided into two main groups of diagonal-grain and spiral-grain failures. Diagonal grain is a deviation of the plane of the annual rings from parallelism with the longitudinal axis of a piece of wood or board. Spiral grain is a deviation of the direction of the fibers in the plane of the annual rings from parallelism with the longitudinal axis of a piece of wood or board. Often spiral grain is not detected during grading. It may substantially weaken timber subjected to static bending.

The strength of a scarf joint subjected to "direct tension" depends, among other things, on the type of species used, effect of slope, hook and/or end steps, effect of grain alignment, relative grain slope, knots present in scarf, machining, and type of adhesive used. The effect due to type of species is of no concern in this testing program. That due to slope is a constant in the tests conducted (beams B-1 to 10 are excluded). The effects due to machining and type of adhesive used are assumed to be constant for the test beams. The effects due to the presence of hooks and end steps are discussed later.

End-grain gluing is more difficult than side-grain gluing. Scarfs cut "against" the grain tend to be weaker than scarfs cut "along" the grain. If diagonal grain is present the scarfing operation will reveal a maximum of end grain in a flat-sawed piece of wood. If spiral grain is present the scarfing operation will reveal a maximum of end grain in a quarter-sawed piece of wood. It is assumed that scarfing is performed "against" the grain. The resulting effect is the same as if the slope of the scarf were increased by a proportionate amount. This is known as the effective slope of scarf and is a combination of the actual slope of scarf and the slope of the grain. The steepness of the effective slope of scarf may often produce early failure. Generally, in commercial practice about one-half of the scarfs are cut against the grain.

The presence of knots further weakens a lamination. If knots are not allowed in scarf joints a failure away from the scarf is very probable.

From the foregoing discussion it follows that the occurrence of scarf failures *versus* other types of tension failures depends on a combination of circumstances, and that scarf joints can be

stronger than the material joined together, the strength of one "continuous" lamination being subject to variation along its length.

A preponderance of scarf failures was noticed in groups 2-B-1 to 10 and 3-B-1 to 10, whereas the opposite was true for groups 2-A-1 to 10 and 3-A-1 to 10. In group 1-A-1 to 11 scarf and other failures were almost equally balanced. Beams B-1 to 10 were randomly assembled by the manufacturer, the primary modes of failure being described in Table 2. The influence of the waxpaper on the mode of failure is clearly shown in Table 10 (beams of the second section).

An examination of the "lines of failure" disclosed a high percentage of wood failure. Peeling of the bottom laminations was observed, particularly in groups 2-B-1 to 10 and 3-B-1 to 10 (Fig. 5). It must be mentioned, however, that peeling in the scarf joint in the second lamination, adjacent to the failed scarf joint, was infrequently observed. The adequacy of the glue joint was further exemplified by the beams failing in horizontal shear. The failure surface extended through several laminations.

STATISTICAL ANALYSES

Beams of First Section (81 beams)

The flexural stress at ultimate failure is considered as a basis for analysis (modulus of rupture). Due to the occurrence of the various types of failures, the group averages for the various groupings of beams cannot be considered as representing the strength-reducing qualities of scarf pattern and/or scarf profile when compared with the group average of the control beams. For purposes of analysis the failures were divided into two major groups — scarf failures and other failures — within each grouping of beams. The groups designated "other failures" comprised all tension failures. Horizontal shear failures were excluded from the analysis.

The well-known statistical *t*-test was employed for the following purposes:

1. To investigate whether the three types of scarf pattern and/or two types of scarf profile significantly influenced the modulus of rupture of the beams characterized by "other failures," and whether there was a significant difference as to the influence of each scarf pattern and/or scarf profile.

2. To investigate the same variables described in Item 1 for the beams characterized by "scarf failures."

3. To investigate where the combining of "other failures" and "scarf failures" within each grouping of beams was permissible.

The following results were observed (corresponding to Items 1, 2, and 3):

1. Other failures. At the 1 percent level the beams containing end joints and grouped together in groups designated "other failures" differed significantly from the control beams as to their influence on the modulus of rupture. At the 5 percent level there was no significant difference between the three types of scarf pattern (Fig. 1). At the 1 percent level there was a significant difference between the beams built up of ⅝-in. and ¾-in. lams containing scarf joints arranged according to pattern 2 as to their influence on the modulus of rupture. This difference was significant at the 5 percent level for the beams of pattern 3. Each of the three groups of beams built up of ⅝-in. lams was compared to the two groups of beams built up of ¾-in. lams. It is interesting to note that there was no significant difference at the 5 percent level for beams built up of ⅝-in. lams (pattern 1) and beams built up of ¾-in. lams (pattern 3).

2. Scarf failures. At the 1 percent level there was a significant difference between beams containing end joints and the control beams. At the 5 percent level there was a significant difference between patterns 1 and 2 for beams built up of ⅝-in. lams as to their influence on the modulus of rupture. At the 5 percent level there was a significant difference as to the influence of patterns 2 and 3 on the modulus of rupture of the beams built up of ¾-in. lams. Based on patterns 2 and 3, there was a significant difference as to the influence of the beams built up

of 5/8-in. and 3/4-in. lams. Each of the three groups of beams built up of 5/8-in. lams was compared to the two groups of beams built up of 3/4-in. lams. For all cases significant differences were observed. Values of t at or above the 5 percent level were considered significant.

3. A comparison of "scarf failures" *versus* "other failures" indicated significant differences at the 1 percent and 5 percent levels for groupings of beams 2-A-1 to 10 and 2-B-1 to 10, respectively.

Reference is made to Table 3 for average values of "scarf failures," "other failures" or a combination of both for each grouping of beams. The statistical t-tests conducted have disclosed a significant difference between "other failures" occurring in beams containing scarf joints and the jointless control beams. The comparison was based on sample averages. Further, there were differences in the tension failures occurring among the groups of beams built up of 5/8-in. and 3/4-in. lams. These differences were obtained from a comparison of the beams of patterns 2 and 3. The 5/8-in. and 3/4-in. lams were selected from the same population of lumber (1 in. nominal size), the difference in lam thickness being achieved through planing. It was concluded that tension failures in beams containing hooked scarfs and in beams containing hooked scarfs with end steps were affected by the presence of scarfs. Hooked scarfs with end steps seemed to exert a more pronounced effect than hooked scarfs without end steps, basing the comparisons on patterns 2 and 3. A t-test confirmed that lamination thickness does not affect the modulus of rupture. This conclusion was drawn from the comparison of the two types of control beams.

A comparison of the "scarf failures" of the groupings of beams disclosed a significant difference between scarf patterns 1 and 2 (5/8-in. lams) as to their effects on the modulus of rupture. A significant difference was also disclosed from a comparison of patterns 2 and 3 (3/4-in. lams). A comparison of patterns 2 and 3 based on beams built up of 5/8-in. lams was not significant. This was probably due to only two beams failing in the scarf (bottom lam) in grouping 3-A-1 to 10, whereas four is the corresponding figure for grouping 2-A-1 to 10. The difference in the sample averages was 396 psi. The corresponding figure for groupings 2-B-1 to 10 and 3-B-1 to 10, disclosing a significant difference, was 302 psi. The latter comparison was based on a total of 14 beams. Examination of the sample averages for the various groupings of beams indicates the superiority of pattern 2 over patterns 3 and 1, respectively. Significant differences between "scarf failures" and "other failures" within groupings of beams could be observed in two instances.

Table 5 is a summary of the moduli of rupture and strength ratios for the various groupings of beams. Strength ratios corresponding to "scarf failures," "other failures," and a combination of these failures, are given. An F-test, based on the analysis of variance and a mixture of tension and scarf failures, permitted the combining of beams with differing scarf patterns and similar end joints into one single group. The decrease in the strength ratio corresponding to grouping 2-A-1 to 10 is noteworthy. If the strength ratio in this group is based on "scarf failures," a value of 0.840 is realized. A mixing of "scarf failures" with "other failures" resulted in a strength ratio of 0.779. The value corresponding to the mixing of groupings 2-A-1 to 10 and 3-A-1 to 10 was 0.781. As can be seen, the average flexural stress at ultimate failure and corresponding strength ratio was reduced in this case upon the mixing of failures and tallying of groupings. The reduction (5.9 percent) was the largest in Table 5 and can largely be attributed to the presence of knots, and in particular to spiral-type cross-grain. It is difficult to control the presence of spiral grain by visual grading, therefore the values in Cols. 8 and 9 of Table 5 are considered more or less representative of manufacturing conditions.

The modulus of elasticity values were computed by utilizing the slopes of the load-deflection curves. A statistical anal-

ysis based on the F-test was made, but has not been included.

Estimates of the lower exclusion limits for values of moduli of rupture for the various groupings of beams are given in Table 6. In Table 9 the test results are compared with design stresses specified by the CSA 0122-1953 specification. Two factors must be applied to the lower exclusion limits in order to bring the test results to a comparable basis with the basic stresses quoted in Table 1 of the specification, modified as to strength-reducing characteristics. The traditional long-term loading factor (9/16) and a net factor of safety were applied.

Beams B-1 to 10 were randomly assembled by the manufacturer, and are reasonably representative of manufacturing conditions, at least for one laminating plant, except that there were no scarf joints in the outside laminations in the region of maximum flexural stress. On the other hand, cross-grain failures were present which easily could result in the failure of a beam, prior to the failure of a scarf joint located in the bottom lam. Grade C was the lowest grade employed for the outside laminations of the beams. End jointing was achieved by employing hooked scarfs of slope 1 in 10 except for some butt joints in interior lams. In view of the foregoing conditions, a "minimum" factor of safety might be used. The beams assembled by the experimentors were subjected to more rigid control, consequently a larger factor of safety was used to make an allowance for this and to bring the manufacturer's and experimentors' beams to an approximately comparable basis. This factor of safety was considered to be equal to 1.5 to 1.67.

If the maximum strength-reducing characteristics permitted by the CSA 0122-1953 were assumed to be present, the computed I_{net}/I_g ratio would be 71.4 percent. The statistical analysis of the knot distribution based on field data from 160 boards disclosed a lower tolerance limit of 84.3 percent. As no other inherent imperfections were present, this indicated that the grading of the lumber (particularly for grade B) was on the high side. The ratio 84.3 percent is conservative and the true value applicable to the test beams is intermediate, say 90 percent,* with respect to the 84.3 percent limit and the sample average of 95.5 percent. The ratio 90 percent applied to the basic stress of 2940 psi given in Table 1 of the CSA 0122-1953 specification furnished a design stress of 2646 psi. This compares favorably with the design stress of 2600 psi derived from the modulus of rupture of the control beams and corresponding to a net factor of safety of 1.67. The percentages to be applied to the basic stress 2940 psi for the various groups of beams are shown in Col. 6 of Table 9.

In all instances, the control beams excepted, where the knots are controlling, the percentages are based on computations considering one notch in a scarf joint as ineffective in transferring stress, and additionally considering the presence of knots in continuous lams at that particular cross-section. The resulting design stresses seem to be too liberal in comparison with the corresponding design stresses obtained from the testing of the various groups of beams. It must be emphasized, however, that designs generally are based on the assumption that the maximum allowable defects within each grade used are present. In the case of an I_{net}/I_g ratio corresponding to 71.4 percent, the resulting design stress would be $2940 \times 0.714 = 2100$ psi, which does not include any reductions due to end jointing.

Beams of the Second Section (*70 Beams*)

Due to the large number of subgroups and the few beams available, the experiment as a whole is of necessity insensitive. Nevertheless, trends are indicated. Referring to Figure 7, it is seen that there is a significant difference at the 1 percent level in the load-carrying capacity of groups 2-a-1 to 5 and 3-c-1 to 5, whereas no significant difference is noticeable between the latter group and group 2-d-1 to 5. There is no significant difference between the load-carrying capacity of

* Tests (5) have shown that $\frac{I_g - I_{\text{knot}}}{I_g} = 0.911$ corresponds to a modulus of rupture = 8953 psi.

groups 2-a-1 to 5 and the control beams. A similar relationship exists between beams of groups 3-a-1 to 5, 1-c-1 to 5, and 1-d-1 to 5. It is noticeable that there is a significant difference at the 1 percent level between groups 1-d-1 to 5 and 2-d-1 to 5, whereas no significant difference is noticeable between groups 1-c-1 to 5, 2-c-1 to 5, and 3-c-1 to 5. There is a significant difference between groups 2-c-1 to 5 and 2-c′-1 to 5, as to their load-carrying capacity. It is interesting to note that there are no differences in load-carrying capacity between groups 1-c-1 to 5, 1-d-1 to 5, 2-c-1 to 5, 2-ac-1 to 5, and 2-acd-1 to 5.

In spite of the fact that the analysis does not distinguish between the various modes of failure, these results emphasize the need for further testing. The various modes of failure are described in Table 10.

CONCLUDING REMARKS

Tests carried out at the University of Alberta (*3, 4*) seem to support the results disclosed by the first 81 test beams as relating to the stress-concentrating effect of end steps and modes of failure.

Tests (*3*) based on 60 beams (2½ in. wide, 7 ¾-in. lams deep, and 12 ft long) among other things brought to the fore that beams containing one unmatched hooked scarf joint with end steps (hook = 0.09 in., end steps = 0.130 in. and slope of scarf = 1 in 14) in the center of the bottom tensile lam were characterized by a strength ratio equal to 0.61. This is comparable to the strength ratio 0.677 in Table 5. The difference in the values can probably be attributed, among other things, to the difference in the end steps, and grade of lumber used. It is remarkable that although the University of Alberta beams contained only one scarf joint in the bottom lam and the University of Toronto beams contained scarfs throughout the beam, the former were still characterized by a lower strength ratio.

Another set of tests (*4*) based on 75 beams (2⅜ in. wide, 7 ¾-in. lams deep, and 12 ft long) disclosed that spiral grain, simple tension or compression failures may terminate the load capacity of a beam before the scarf joint has failed. These beams contained one unmatched plain scarf joint (slope 1 in 12) in the center of the bottom tensile lamination. Failures at the scarf were compared to the average strength of the control beams. A strength ratio equal to 0.82 resulted. The strength ratio based on scarf failures occurring in group 2-A-1 to 10 equals 0.84. The corresponding figure for group 3-A-1 to 10 is 0.795. The latter two strength ratios compare very favorably with the value 0.82.

In conclusion it must also be mentioned, however, that when the outside end step in the case of the University of Alberta test beams (*3*) was planed away no significant difference in the moduli of rupture of the beams containing the scarf joint and the jointless control beams could be observed. The same conclusion was arrived at when the roughness of the feathered end of the plain scarf was planed away. This seems to suggest that a considerable increase in the strength of a beam containing scarf joints may be expected if the exterior surface of the extreme top and bottom lams is planed in such a manner as to remove any unevenness at the tip of a scarf, and no delamination is assumed to occur. Further testing is needed to confirm this.

CONCLUSIONS

1. The presence of spiral-type cross-grain and knots, rather than the strength of scarf joints, may limit the load capacity of laminated beams subjected to bending forces. It is, however, of importance to notice that the presence of scarf joints arranged according to patterns 1, 2 and 3 influences the modulus of rupture of the test beams characterized by other than scarf failures (shear failures excluded).

2. The stress-concentrating effect of the end steps in a scarf joint is clearly observed in this experiment. The lowest strength ratio, obtained from series 3-B-1 to 10 and based on scarf failures, is 0.663.

3. The hook in a hooked feathered scarf joint seems to possess little stress-concentrating effect.

4. The resulting design stresses (Table 9), pertaining to the use of the test beams under dry service conditions and subjected to long-term loading, are below the corresponding stresses estimated according to the "CSA 0122-1953 Specification for Glued-Laminated Timber Construction," probably because the specification does not make proper allowance for the stress-concentrating effect of end steps in scarf joints.

5. No harmful influence could be detected on the glue line due to creosote and the pressure treatment.

6. The tests investigating the effect of delamination on the strength of laminated beams tested in flexure are too few in number to permit general quantitative deductions, but qualitative trends are indicated nevertheless, showing the serious effects of delamination. Further testing is needed.

REFERENCES

1. Tamberg, K. G., "An Experimental Study as to the Use of Glued Laminated Timber for Bridge Beams." Thesis, Univ. of Toronto (1958).
2. Fox, S. P., "An Investigation into the Effects of Certain Variables in Scarf-Jointed Timber Laminations." *Forest Prod. Jour.,* 6:No. 10 (Oct. 1956).
3. Edlund, R. C., "A Study of Some Factors Affecting the Action of Hook Scarf Joints in Laminated Wood Beams." Thesis, Univ. of Alberta (1957).
4. Stieda, G. K. A., "An Investigation into the Strength-Reducing Effects of Plain Scarf Joints in Laminated Wood Beams." Thesis, Univ. of Alberta (1958).
5. Morrison, C. F., "Research on the Structural Use of Glued Laminated Timber." Building Research Congress (1951).
6. Newlin, J. A., Heck, G. E., and March, H. W., "New Method of Calculating Longitudinal Shear in Checked Wooden Beams." U.S. Dept. of Agric. Approved Tech. Article (1934). Revised ed. (1955).