BOLT-BEARING STRENGTH OF WOOD AND MODIFIED WOOD

EFFECTS OF DIFFERENT METHODS OF DRILLING BOLT HOLES IN WOOD AND PLYWOOD

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BOLT-BEARING STRENGTH OF WOOD AND MODIFIED WOOD

Effects of Different Methods of Drilling Bolt Holes in Wood and Plywood[1, 2]

By

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Summary

Studies at the Forest Products Laboratory have demonstrated that many factors affect the behavior of a bolt in bearing on a block of wood or plywood. When such variables as the type, diameter, and bearing length of the bolt and the species, dimensions, and moisture content of the specimen are eliminated, there still remains a wide variation in bolt-bearing behavior that can best be ascribed to the characteristics of the bolt hole as affected by different methods of drilling. Two of the more important variables are the type of drill used and the rate of feed when drilling.

Analysis of the 259 bolt holes covered by this report indicates that (1) bolt holes with visibly smooth side walls have bolt-bearing properties far superior to those with visibly rough side walls; (2) in order to produce a smooth hole, the drill must be well sharpened and the rate of feed in drilling must be slow enough to enable the drill to cut rather than tear its way through the piece; and (3) in the materials used in this study, Douglas-fir plywood and Sitka spruce, the twist drill produces a smoother hole than does a machine bit. Because the area of wood in actual contact with the bolt is reduced, a bolt hole with its wall visibly scored or with material torn or otherwise removed beyond the true cutting line of the drill will be more seriously deformed at loads less than the proportional limit, will have a lower load at proportional limit and a reduced ultimate load, and will be more seriously deformed at the ultimate load than a hole

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[1]This mimeograph is one of a series of progress reports prepared by the Forest Products Laboratory to further the Nation's war effort. Results here reported are preliminary and may be revised as additional data become available.

[2]This is the first of a series of reports dealing with bolt-bearing strength of wood and modified wood. Other reports will be issued as data become available.

with a smooth, truly drilled wall. Poorly drilled holes thus introduce variables which make it difficult if not impossible (1) to conduct a testing program involving the effects of small variables or (2) to justify the use of the common design assumption that the load on a multiple bolted connection is equally divided among the bolts.

Bolt holes must be properly drilled if the allowable bolt-bearing loads presented in the ANC Design Handbook[3] are to be used. For a poorly drilled hole, the stress at the proportional limit may be as low as one-third of the allowable limit stress thus computed, and the additional deformation will greatly increase the distortion of the associated structure.

Introduction

This study of bolt holes was undertaken primarily to improve the test procedure employed in a comprehensive investigation of the bearing strength of plywood under steel aircraft bolts. The earlier tests in that investigation displayed unaccountable variations in behavior which, in many cases, were of sufficient magnitude to obscure the effect of the variables under study. Examination disclosed that most of those bolt holes had visibly rough side walls. The purpose of this investigation was to ascertain if holes with smooth side walls could be drilled consistently in plywood and if such holes would result in consistently improved bolt-bearing properties.

Results of these tests demonstrated the advisability of studying desirable methods of drilling bolt holes in solid wood before undertaking an investigation of bolt-bearing strength of solid wood reinforced with various thicknesses of plywood and compreg. Accordingly, such tests were included.

This study is readily divisible into three phases. In the first or exploratory stage, experimental holes indicated the combinations of factors which produce a smooth or a rough hole[4]. In the second phase, visual examination was employed to isolate and study the individual factors. In the third phase, bolt-bearing tests were made to secure load-deformation curves for rough and smooth holes.

Materials

The plywood used in the tests was commercial, 65-35, seven-ply, 3/4-inch exterior Douglas-fir. All bolt-bearing specimens were at least

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[3] ANC Handbook on the Design of Wood Aircraft Structures. 1942.

[4] Detailed analysis of this first phase has not been included in this report because the second phase covers the same points in much greater detail.

4-1/2 inches wide by 5 inches long, and the bolt hole, 1/4 inch in diameter, was located 2 inches from one end and equidistant from the two sides. These dimensions were considered ample to develop the full bearing strength of the plywood.

The solid wood used in the tests was Sitka spruce. All bolt-bearing specimens were 2 by 2 by 4-1/2 inches, and the bolt hole, 1/2 inch in diameter, was located 2-1/4 inches from one end and equidistant from the two sides. These dimensions were also considered adequate to develop the full bearing strength of the wood.

Steel aircraft bolts were used in all of the bolt-bearing tests. For convenience, and in order to facilitate comparison of the results with those of other tests, 1/4-inch bolts were used in the plywood specimens and 1/2-inch bolts in the solid wood.

Matching

Comparable plywood specimens for both visual-examination and bolt-bearing tests were end matched as to face grain to secure maximum uniformity of material within each series of specimens. All bolt-bearing specimens were cut from the same panel of plywood.

Comparable solid wood specimens for visual examination were end matched. The bolt-bearing specimens were end matched from a single piece and numbered consecutively from one end. Those with odd numbers constituted one series of specimens and those with the even numbers the other series. Any variation in material was thus minimized.

Drilling Procedure

Before drilling the bolt holes covered by this report, about 500 experimental holes were drilled. The drills employed included several sizes of twist drills with approximately 60° and 120° points, machine bits with slow and fast spirals, and Foerstner bits. Drills used (fig. 1) represent types in common use. The speeds explored ranged from 200 to 4,000 revolutions per minute and the rate of feed from 1/2 inch to 100 inches per minute.

In the exploratory tests some of the twist drills were sharpened on a bench grinder by an experienced machinist and some on a mechanical drill grinding machine. Twist drills thus sharpened were tried at different speeds in both solid wood and plywood.

All holes were drilled on a drill press with a hand feed.

The procedure used in drilling the specimens covered by this report is shown in table 1 and in figures 2 to 4. The rate of feed employed in series 6 might appear to be unduly high, but the resultant holes were no rougher than some of similar dimension observed in commercially produced wing spars as illustrated in figure 5.

Minor Tests

Since this was an exploratory operation in which the element of time was of considerable import, no accompanying minor tests were made, and the specimens were not conditioned.

Visual Examination of Bolt Holes

Holes which showed pronounced characteristics, either good or bad, were photographed. These photographs constitute a part of this report.

Bolt-bearing Tests

Compressive loading was employed in the bolt-bearing tests and the grain of the wood or of the face ply of the plywood was parallel with the direction of load. Figure 6A shows a plywood specimen in the testing apparatus. The apparatus for the solid wood specimen was identical, except that the space between the vertical metal members supporting the ends of the test bolt was increased to accommodate a thicker specimen.

The displacement of the bolt in all tests was measured by means of a 1/10,000-inch dial mounted as shown in figure 6A. The displacement thus measured is actually the displacement of the bottom of the specimen relative to the bed of the testing machine and therefore includes the deformation of the testing equipment and of the portion of the specimen below the bolt hole. These factors, however, constituted such a small percentage of the deformation recorded by the dial that they were disregarded in these tests.

Figure 6B shows the recessed inner face of a typical interchangeable bushing used in the vertical supports to accommodate bolts of different diameters. Exploratory tests simultaneously conducted in the general study of bolt-bearing strength of wood and modified wood had demonstrated that as the displacement of the bolt increases, the wood fibers tend to spread out along the loaded surface of the bolt unless restrained. These tests demonstrated also that, while the introduction of such restraint has but little if any effect on the proportional limit (presumably because it occurs after the proportional limit is reached), it does have a marked effect on the ultimate load. This effect appears to be due to the addition of the friction of the extruded fibers against the test equipment and to the increase in effective bearing area caused by the compaction of the wood fibers immediately above the bolt. By using the bushing shown, the bolt is supported at the face of the specimen, but there is no lateral restraint imposed on the wood fibers above the bolt. In order to minimize initial friction between the specimen and the bushing, the nut was omitted and the bolt withdrawn slightly. The bolts were inspected at frequent intervals, and those found to be permanently deformed were immediately discarded.

Discussion of Results

Exploratory

In drilling the experimental holes to establish drilling technique, the 120° (probably actually 118°) twist drill appeared to produce the smoothest hole. The 60° twist drill was about equally effective, but offered no apparent advantages over the more common 120° drill. A hole drilled with a machine bit with a slow spiral did not appear to differ materially from one drilled with a machine bit with a fast spiral, or from one drilled with a Foerstner bit.

Visual Examination

Drills used for the visual-examination and bolt-bearing tests were therefore limited to the 120° twist drill and the machine bit, the latter of which is recommended in Wood Aircraft Inspection and Fabrication, ANC Bulletin 19, for holes in solid wood and had been employed in previous bolt-bearing tests in plywood at the Forest Products Laboratory. A machine bit with a slow spiral was used in preference to one with a fast spiral because the former appeared to be sturdier and therefore better suited to high-speed production work.

Figure 2 shows the effect of the type of drill and rate of feed on the appearance of holes drilled in Douglas-fir plywood. The specimens shown in figure 2B were end matched, and the holes shown in each specimen were drilled 1 inch distant from the holes in the adjacent specimen. The hole produced with the 120° twist drill with slow feed is the smoothest, that with the machine bit with slow feed rougher, that with the machine bit with fast feed still rougher, and that with the twist drill with fast feed is the roughest.

The machine bit and the Foerstner bit had a tendency to produce large chips which sometimes wedged underneath the horizontal cutting edge. Some of the chips were complete washers in form, the full diameter of the drill in size, up to 1/32 inch thick, and strong enough to remain intact when the bit was withdrawn. In a few cases a chip became wedged between the side of the bit and the wall of the hole and scored the wall. It was found that large chips are frequently produced just above a glue line or plane of local weakness (fig. 3). The specimens in figure 3 were end matched, and the holes shown in each specimen were drilled 1 inch distant from the holes in the adjacent specimen in the same photograph.

The specimens in figure 3 were drilled at 800 instead of 500 revolutions per minute, as were those in figure 2. This was due to the use of a different drill press having a much more sensitive feed which facilitated the detection of chips wedged under the bit.

When a chip wedges underneath the cutting edge of a machine bit, the drill can be cleared by increasing the feed pressure sufficiently to enable the cutting edge to penetrate the chip. If a hand-feed bit is thus cleared, the necessary increase in feed pressure will frequently cause the bit to plunge through an appreciable distance at a high rate of feed the instant it is cleared and before the added pressure can be relieved. Such a sudden advance will produce coarse chips and may tear fibers outside the cutting line. The alternative is to stop the bit and remove the chip before resuming drilling. The latter procedure is to be preferred, but it involves so much lost time that its commercial use is highly improbable. It has a further disadvantage in that exact register is difficult as drilling is resumed.

Coarse chips, produced by breaking up "washers" lodged underneath the horizontal cutting edge of a machine bit or by fast feed of a machine bit or twist drill, demonstrated a greater tendency to clog in the flutes and to score the side walls than did the finer chips. Also, the larger the chips, the greater was the damage to the wall of the hole.

Figure 4 shows the effect of type of drill and rate of feed on the appearance of holes drilled in Sitka spruce, and is comparable with figure 2. The holes were drilled as were those in plywood. The order of smoothness of the holes produced by the four methods of drilling is the same in Sitka spruce as in Douglas-fir plywood.

Bolt-bearing Tests

Table 1 lists the bolt-bearing properties obtained from the tests. Figures 7 and 8 show typical solid wood specimens after test. Since these photographs are of the undisturbed, nonloaded side of the bolt hole, they represent the appearance of the loaded side of the hole before test. Figures 9 and 10 show composite load-deformation curves for each series.

The data in table 1 and the curves in figures 9 and 10 indicate that the method of drilling affected the bolt-bearing properties for all loads up to and including the ultimate load. The curves in figure 9 represent series 1 through 4 of table 1; those in figure 10 represent series 5 and 6. The stress at proportional limit and the deformations at all loads were affected to a much greater degree than the ultimate load.

It is significant that the specimens in series 3 of table 1, wherein the smoothest holes were obtained, had the highest stress at proportional limit and the lowest deformations of any of the plywood series (fig. 9). Similar effects are apparent in series 5 as compared with series 6 of table 1 for the tests of wood specimens (fig. 10).

A comparison of series 1 with series 3 of table 1, wherein the only variable is the type of drill, indicates that series 3 is superior to series 1 with an increase of more than one-third in the stress at proportional limit and a decrease in deformation. No great significance is attached to the slightly lower ultimate obtained for holes drilled with a twist drill. The results of other tests indicate that this is accidental rather than typical.

A comparison of series 2 with series 1 of table 1, wherein the speed was increased from 400 to 2,200 revolutions per minute and the rate of feed reduced from 3 inches to 1 inch per minute, using a machine bit, indicates no significant effect of these factors except a reduction in the deformation for series 1. A comparison of series 4 with series 3 of table 1, however, indicates decided advantages in the higher speed and slower feed. The stress at proportional limit was increased almost one-half, while the deformations were reduced considerably. Again there was no appreciable change in the ultimate load.

The combined effects of speed and rate of feed, using a twist drill, are even more apparent in the bolt-bearing tests of solid Sitka spruce in series 5 and 6 of table 1. The peripheral or cutting speeds of the 1/2-inch drill used were roughly comparable to those of the 1/4-inch drills used in series 1 to 4 of table 1. The stress at proportional limit was nearly 200 percent greater for the higher speed and slower feed. The ultimate was increased about one-fifth, while the deformations were reduced about three-fourths. These pronounced effects can probably be attributed largely to the greatly increased rate of feed in series 6 of table 1.

Other more extensive bolt-bearing tests of Douglas-fir plywood currently under way in connection with the comprehensive study of bolt-bearing strength of wood and modified wood have indicated that under conditions of testing which permit developing the full value of stress at proportional limit, the ratio between ultimate and proportional limit usually falls within the range from 1.25 to 1.75. Exploratory tests employing 1/2-inch bolts in Sitka spruce, but with higher ratio of bearing length to diameter, produced ratios of ultimate to proportional limit within the same range. In the tests covered by this report, only those of series 3 and 5 of table 1 representing holes drilled with a twist drill at high speed and low rate of feed and having visibly smooth surfaces produced results falling within this range.

The allowable ultimate bolt-bearing stress under a 1/4-inch steel aircraft bolt in 65-35 Douglas-fir plywood, such as was used in group 1 of table 1, is 5,400 pounds per square inch when computed in accordance with the 1942 ANC Handbook on the Design of Wood Aircraft Structures[5]. Dividing this stress by the ultimate factor of safety, 1.50, the allowable limit value of 3,600 pounds per square inch is obtained. Table 1 shows that such an allowable limit stress exceeds the proportional limit for either series

[5]Computation based on figure 2-30 without reduction for ratio of bearing length to bolt diameter (L/D).

2 or 4 (although the ultimate stresses for those two series were approximately 130 percent of the 5,400 pounds per square inch allowable ultimate stress computed from the Design Handbook), but that such an allowable limit stress does not exceed the proportional limit of either series 1 or 3. The proportional limit of 5,040 pounds per square inch in series 3 is 140 percent of the computed allowable limit stress.

The holes in series 1 to 4 of table 1 were all drilled at a comparatively slow rate of feed. Load-deformation curves of similar tests not included in this report indicate that a further increase in rate of feed would have resulted in even greater deterioration in bolt-bearing properties.

The allowable ultimate and limit stresses for the Sitka spruce of group 2, computed in accordance with the Design Handbook, are 4,400 and 2,950 pounds per square inch, respectively. The proportional limit shown in table 1 for series 5 is slightly higher than that allowable limit stress, while the ultimate is only slightly lower than the Design Handbook value; in series 6, however, the proportional limit is less than 40 percent of the allowable limit stress, and the ultimate is only about 75 percent of the Design Handbook value.

The above bolt-bearing stresses were computed in accordance with the Design Handbook and therefore contemplate a moisture content of 12 percent. Table 1 shows that the average moisture content for the plywood was about 4-1/2 percent and for the Sitka spruce about 10 percent. Thus, despite the benefit of a lower moisture content, series 2, 4, and 6 of table 1 showed proportional limits less than the computed allowable limit stresses. If the tests had been run at the higher moisture content, or the results corrected for the difference, the discrepancies would have been still larger.

Conclusions

1. The rate of feed of the drill has a pronounced effect on bolt-bearing properties of both wood and plywood. Excessively high rates of feed tear out material beyond the true cutting line and damage other fibers in the wall of the hole, thereby reducing the effective bearing area of the bolt. The rate of feed should be low enough to enable the drill to cut rather than tear through the piece. The drill should produce shavings, not chips. Granular chips are evidence that the rate of feed is too high or dangerously close to the upper limit.

2. The type of drill has an appreciable effect on the bolt-bearing properties of both wood and plywood. The twist drill appears to have certain inherent advantages over a machine bit, especially for short holes, in the materials studied. The twist drill under proper conditions produces a hole which has a pronounced "shine."

3. The drill should be rotated at the highest speed compatible with the combination of a smooth hole and reasonable drill life. The twist drill is made without a centering spur and therefore must be carefully

sharpened and centered in the chuck, especially when operated at high speeds. A poorly sharpened or poorly centered twist drill will "chatter" as the cutting lips engage the piece, cutting a rough, enlarged hole which produces irregular bolt-bearing properties. This tendency to chatter becomes more marked as either the speed of rotation or the diameter of the drill is increased.

Regardless of the type of drill used, the higher speeds produce considerable friction, and the heat thus generated may overheat a carbon steel drill, especially when deep holes are drilled. It follows that a drill used intermittently or one used for shallow holes can be operated at a higher speed than one used continuously to produce deep holes. Higher speeds tend to offset, at least partially, the effect of too high a rate of feed and thereby improve what would otherwise be a poor hole.

4. Machine sharpening is to be preferred for twist drills of all sizes, particularly for those of diameters larger than 1/4 inch. The exploratory operations demonstrated that it is difficult to sharpen twist drills larger than 1/4 inch in diameter by hand so that they will not chatter when used at the peripheral speeds of 300 to 400 feet per minute usually recommended by the manufacturers for high speed drills.

5. In general, the combination of factors which produces the smoothest hole will produce the hole with the most desirable bolt-bearing characteristics. The rough hole has a lower proportional limit and a higher deformation for loads less than the proportional limit. If the walls of the hole are badly torn, the ultimate load also is decreased and the accompanying deformation increased.

6. From the standpoint of testing operations, the rough hole is especially serious because of the magnitude of the deviations introduced, particularly in the proportional limit. Such deviations may easily obscure the effect of the variable or variables under study and thereby render the data difficult, if not impossible, to interpret.

7. From the standpoint of use in a structure, the rough or improperly drilled hole has bolt-bearing properties which are far inferior to those of a properly drilled hole. The proportional limit and ultimate load resulting from a poorly drilled hole will be lower than that from a properly drilled hole and the attendant deformation of the bolt hole and distortion of the structure will be much greater.

8. A multiple-bolt connection in which all or some of the holes are poorly drilled cannot be expected to develop or maintain a distribution of loads among the several bolts which follows any predetermined mathematical pattern. The distribution of load in such connections is of necessity predicated on a certain uniformity of action. In series 5 of table 1, with good holes, the average deformation at the proportional limit was 0.015 inch, and at the ultimate, 0.025 inch. In series 6 of table 1, with poor holes, the corresponding deformations were 0.024 inch and 0.151 inch.

9. Allowable bolt-bearing loads presented in the ANC Design Handbook are not applicable unless the bolt holes are properly drilled. The proportional limit for a poorly drilled hole may be as low as one-third of the allowable limit load thus computed. When the proportional limit is less than the allowable limit load, the application of the allowable limit load will result in permanent distortion of the associated structure because such load will slot the bolt holes.

Table 1.--Drilling procedure and resultant bolt-bearing properties

Series	Drill				Appearance of hole	Values for individual specimens						
	Type	Diameter	R.p.m.[1]	Feed[1]		Specific gravity[2]	Moisture content[3]	Proportional limit		Ultimate		Ratio ultimate to proportional limit
								Unit stress	Rate of deformation	Unit stress	Total deformation[4]	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
		In.		In. per min.			Percent	Lb. per sq. in.	In. per 1,000 lb. per sq. in.	Lb. per sq. in.	In.	
						Group 1—Douglas-fir plywood						
1	Machine bit	1/4	2,200	1	Fuzzy	0.508	4.8	3,830	0.00243	7,740	0.0900	2.02
						.517	4.9	3,610	.00269	7,020	.0400	1.94
						.516	4.8	3,610	.00224	8,560	.0700	2.38
						.516	4.9	3,610	.00264	7,560	.0800	2.09
						.528	4.9	3,520	.00276	7,200	.0600	2.05
Average						.517	4.9	3,640	.00255	7,620	.0680	2.10
2	Machine bit	1/4	400	3	Moderately rough	.523	4.0	3,630	.00304	7,820	.1300	2.15
						.520	4.3	3,950	.00387	7,120	.0800	1.80
						.510	4.0	2,190	.00349	6,840	.1400	3.12
						.516	4.7	4,160	.00292	7,180	.0600	1.72
						.508	4.8	3,390	.00280	7,310	.1000	2.16
Average						.515	4.4	3,460	.00322	7,250	.1020	2.09
3	Twist drill	1/4	2,200	1	Smooth	.530	4.6	5,600	.00161	7,540	.0400	1.35
						.523	4.7	5,140	.00120	6,700	.0300	1.30
						.525	4.6	5,040	.00213	7,480	.1000	1.49
						.526	4.6	4,490	.00187	6,860	.0500	1.53
						.497	4.6	4,940	.00241	6,230	.0300	1.26
Average						.520	4.6	5,040	.00184	6,960	.0500	1.38
4	Twist drill	1/4	400	3	Moderately rough	.497	4.2	2,600	.00304	6,160	.0800	2.37
						.525	4.4	2,590	.00316	6,370	.0500	2.46
						.526	4.5	4,090	.00291	7,380	.0600	1.81
						.513	4.5	3,440	.00424	7,040	.1300	2.04
						.531	4.3	4,210	.00315	7,220	.0500	1.72
Average						.518	4.4	3,390	.00330	6,830	.0740	2.02
						Group 2--Sitka spruce						
5	Twist drill	1/2	800	2	Smooth	.404	9.8	3,160	.00505	3,950	.0240	1.26
						.409	9.7	2,860	.00559	3,620	.0260	1.26
						.409	9.9	2,920	.00415	3,560	.0200	1.22
						.405	10.1	2,710	.00406	3,900	.0240	1.44
						.398	10.0	3,620	.00425	4,100	.0220	1.13
						.398	9.9	3,160	.00458	3,880	.0240	1.23
						.397	9.6	3,470	.00450	4,200	.0240	1.21
						.398	10.0	3,160	.00474	4,320	.0240	1.36
						.398	10.0	3,010	.00444	4,160	.0280	1.38
						.398	10.2	3,770	.00364	4,810	.0240	1.27
						.399	10.1	3,020	.00501	4,110	.0260	1.36
						.395	10.3	3,310	.00588	4,260	.0275	1.29
						.399	10.5	3,160	.00524	3,860	.0320	1.22
Average						.401	10.0	3,180	.00470	4,060	.0250	1.28
6	Twist drill	1/2	200	60	Rough	.403	10.0	1,200	.01685	2,540	.0860	2.11
						.407	10.0	800	.01617	3,160	.1000	3.92
						.407	10.2	1,480	.02167	3,530	(5)	2.39
						.398	10.3	900	.02522	2,910	.1600	3.22
						.398	10.0	1,050	.02402	3,030	.1650	2.87
						.395	10.0	1,050	.02335	3,060	.1600	2.90
						.407	10.0	1,660	.01728	4,140	.1400	2.50
						.395	10.2	1,060	.02140	3,490	.1900	3.30
						.396	10.2	1,200	.01892	4,500	[6].1900	3.74
						.398	10.0	1,200	.01516	4,580	[6].1900	3.80
						.397	10.3	900	.03131	2,620	.1300	2.90
						.397	10.3	900	.02767	2,830	(5)	3.13
						.395	10.6	1,050	.02658	3,270	.1550	3.10
Average						.399	10.2	1,110	.02182	3,360	[7].1510	3.03

[1]Approximate.

[2]Specific gravity oven-dry based on volume at test.

[3]Based on oven-dry weight.

[4]Not corrected for zero offset.

[5]Dial stuck.

[6]Last obtainable deformation. Deformation at ultimate beyond capacity of dial.

[7]Includes values qualified by footnote 6.

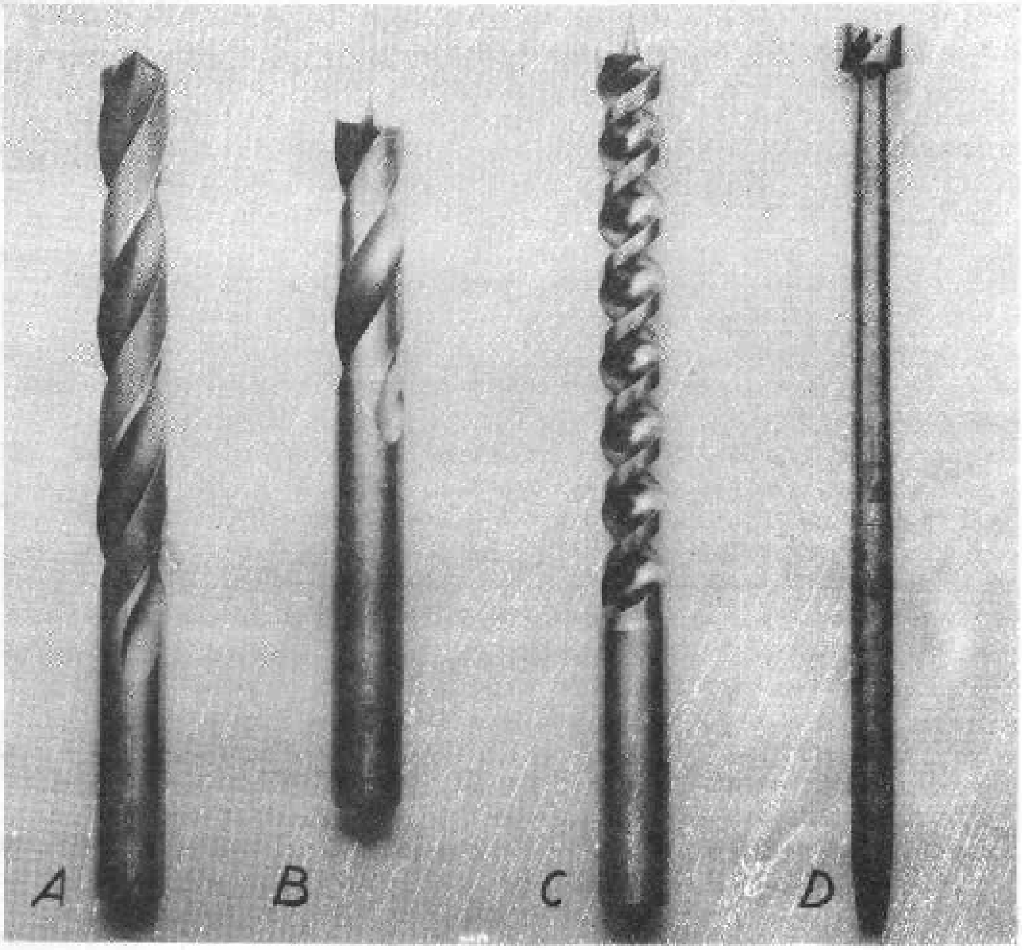

Figure 1.--Typical 1/2-inch drills used in preparation of specimens. A, twist drill with 118° point; B, machine bit with slow spiral; C, machine bit with fast spiral; D, Foerstner bit.

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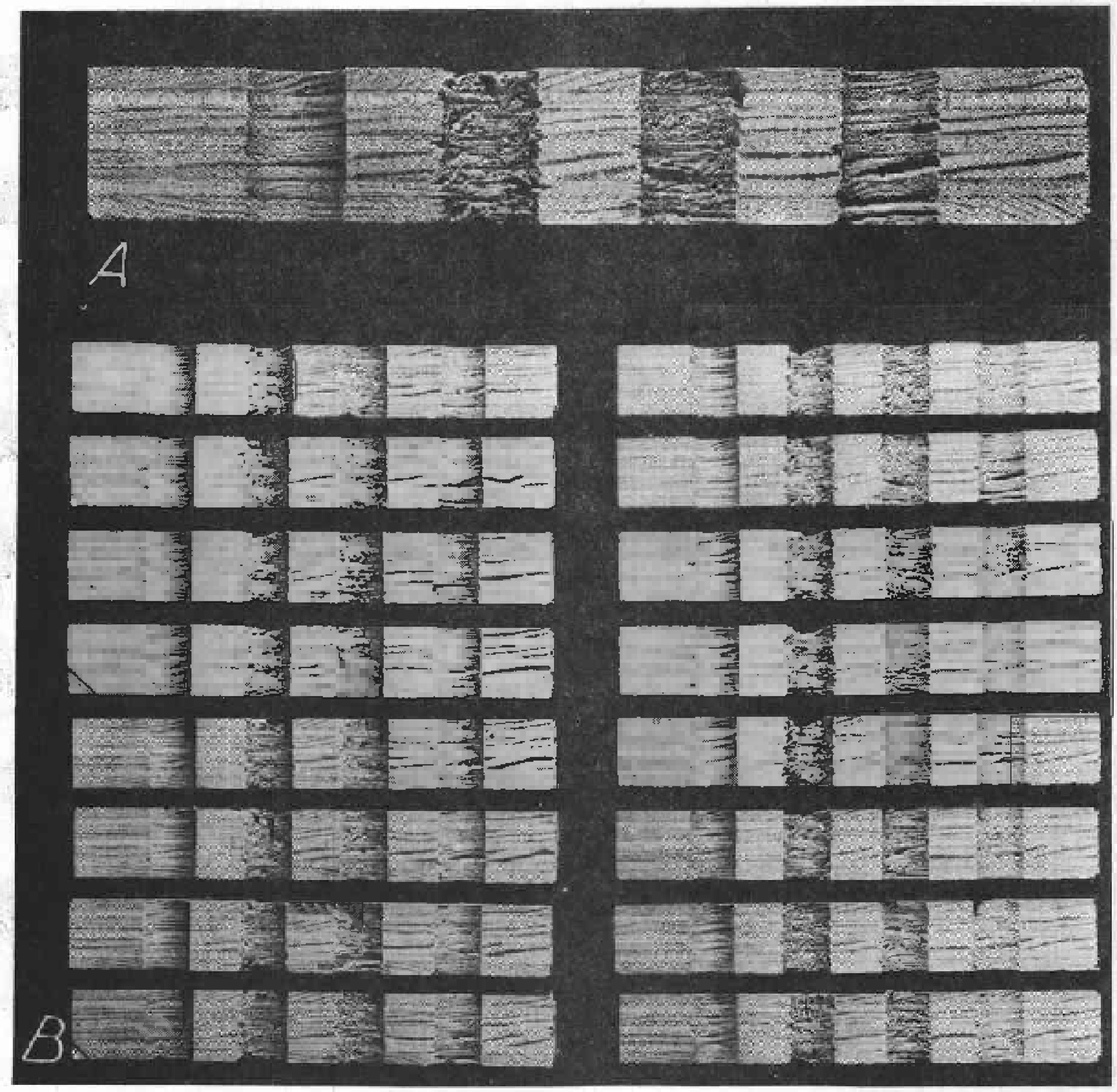

Figure 2.--Effect of type of drill and rate of feed on smoothness of 1/2-inch hole drilled at 500 revolutions per minute in 7-ply, 3/4-inch Douglas-fir plywood. A, left to right: twist drill with feed of 1 inch per minute, twist drill with feed of 20 inches per minute, machine bit with feed of 20 inches per minute, and machine bit with feed of 1 inch per minute. B, end-matched specimens; drilling procedure same as in A.

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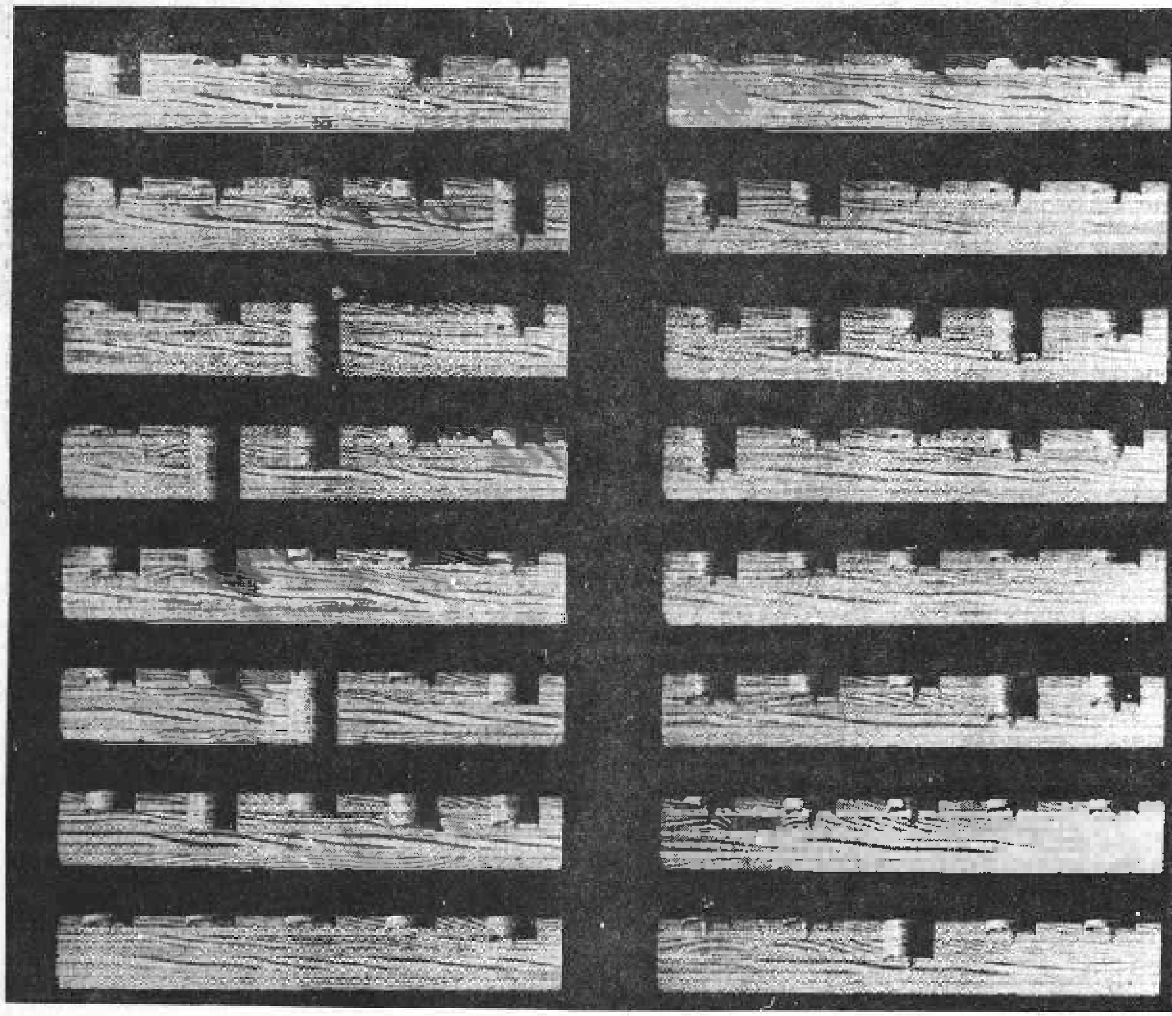

Figure 3.--Location at which chips wedged on cutting edges of machine bit while drilling a 1/2-inch hole in 7-ply, 3/4-inch Douglas-fir plywood at 800 revolutions per minute.

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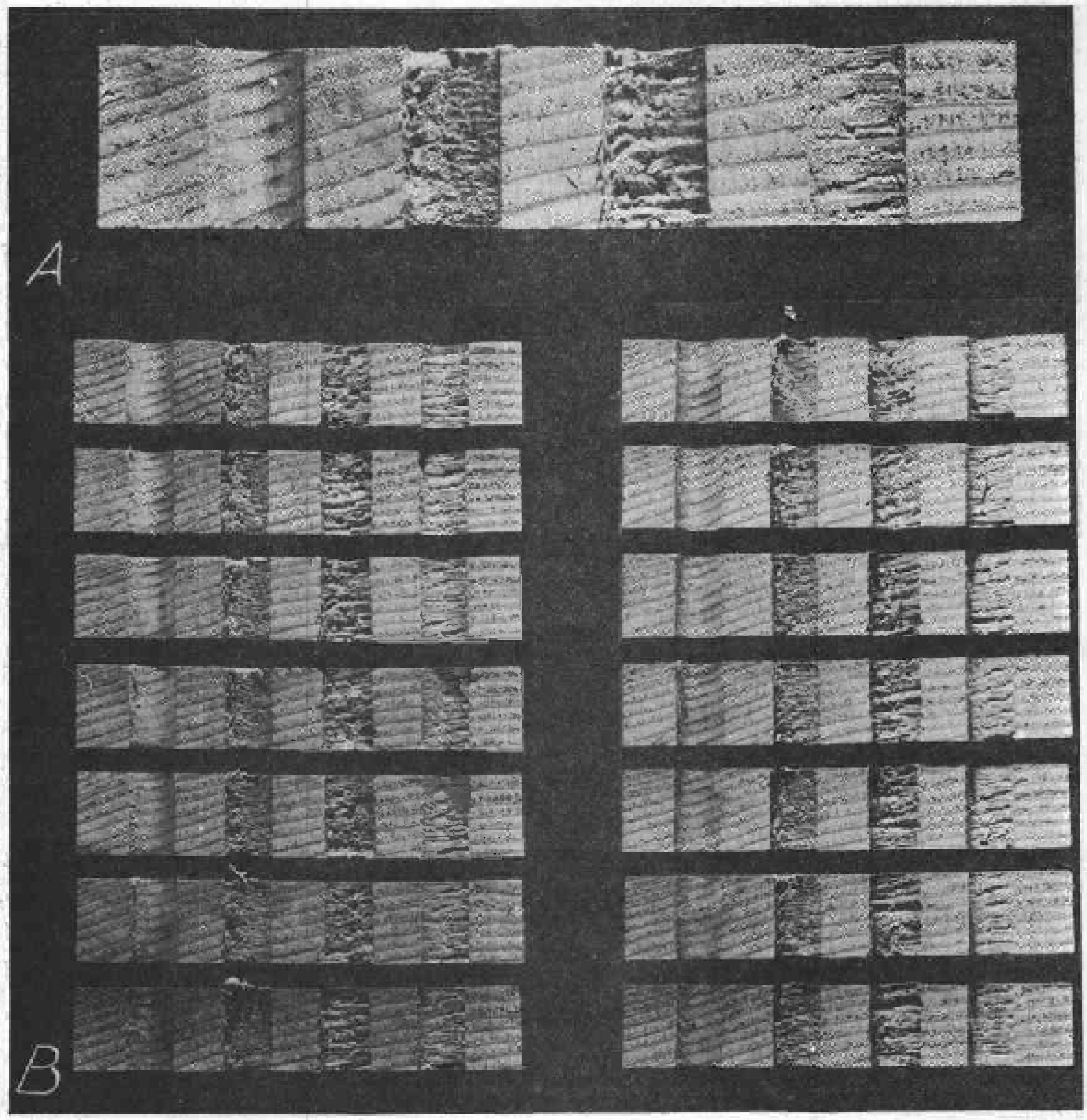

Figure 4.--Effect of type of drill and rate of feed on smoothness of 1/2-inch holes drilled at 500 revolutions per minute in 7/8-inch Sitka spruce. A, left to right: twist drill with feed of 1 inch per minute; twist drill with feed of 20 inches per minute; machine bit with feed of 20 inches per minute; and machine bit with feed of 1 inch per minute. B, end-matched specimens; drilling procedure same as in A.

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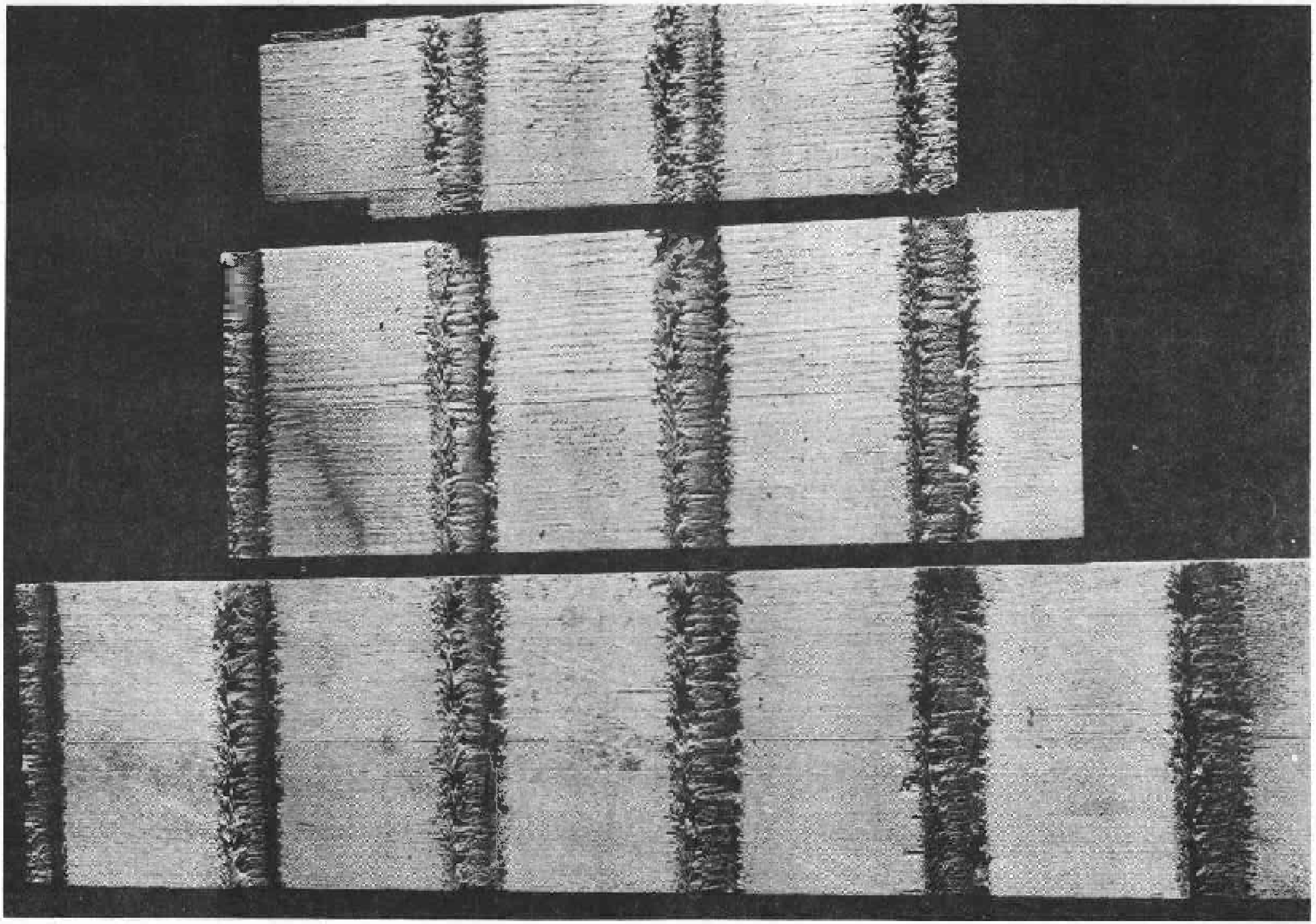

Figure 5.--Rough 9/16-inch holes in commercially produced Sitka spruce aircraft wing spars.

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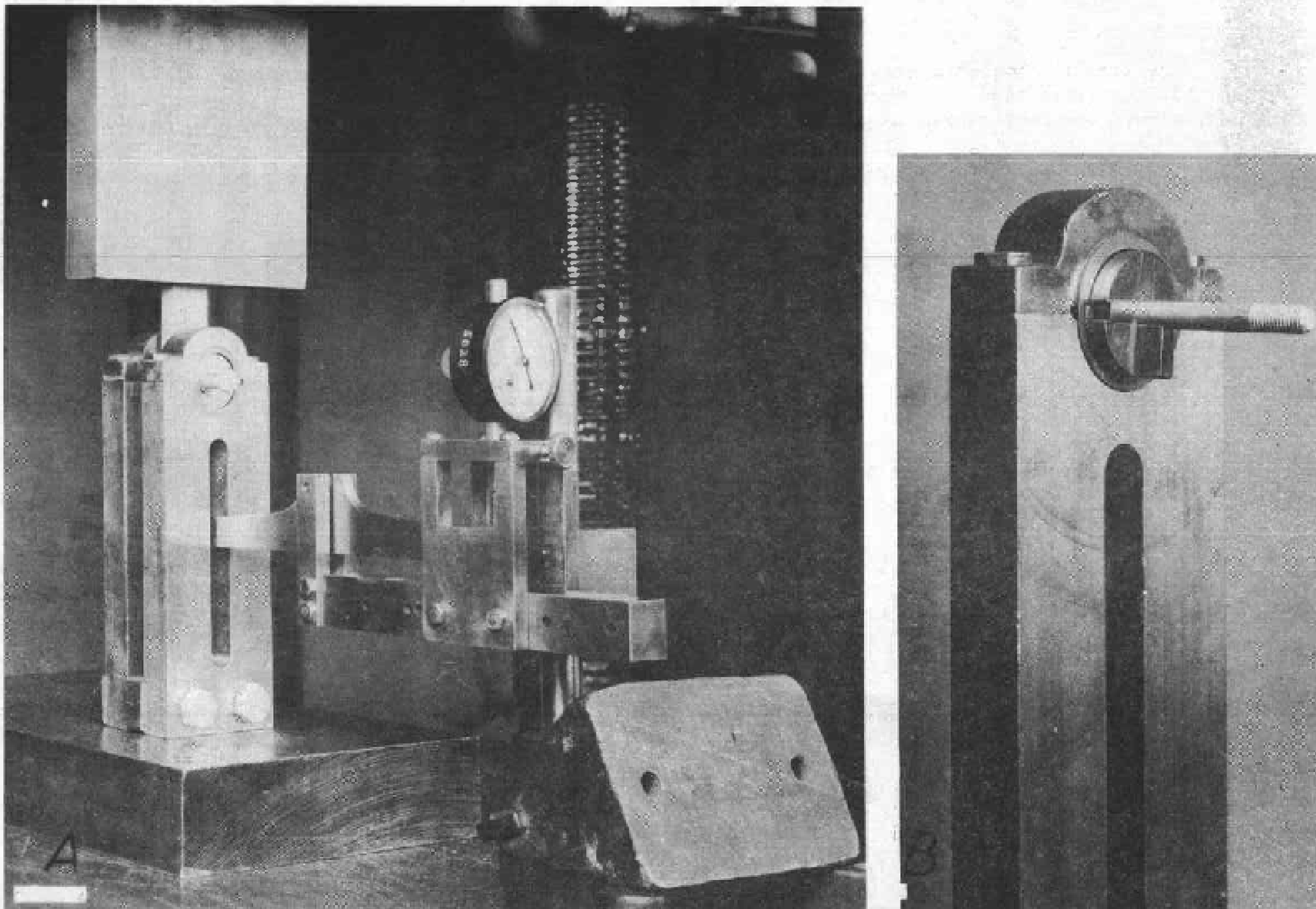

Figure 6.--A, bolt-bearing test in plywood under compressive load. B, recessed bushing in apparatus.

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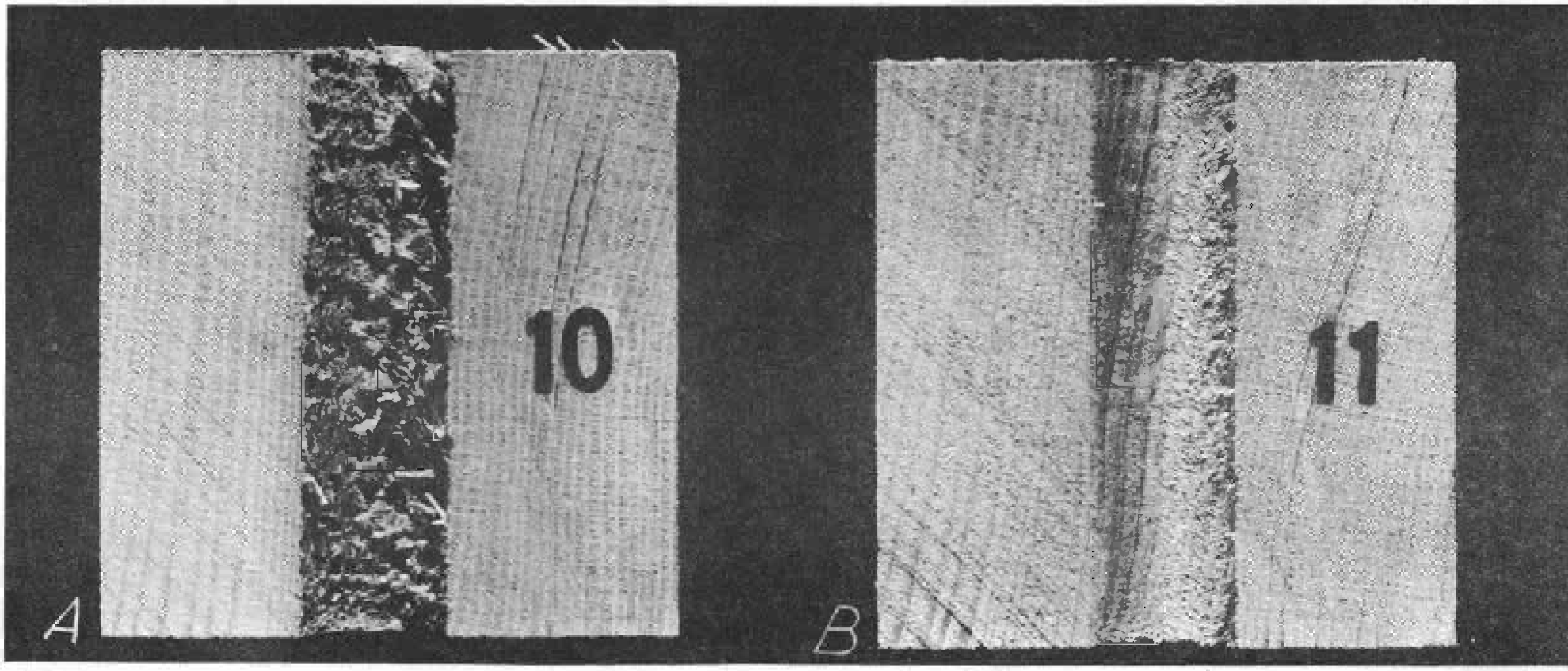

Figure 7.--A, appearance of 1/2-inch hole drilled with twist drill at 200 revolutions per minute in Sitka spruce at feed of 60 inches per minute (series 6, table 1); B, appearance of hole similarly drilled at 800 revolutions per minute in Sitka spruce at feed of 2 inches per minute (series 5, table 1).

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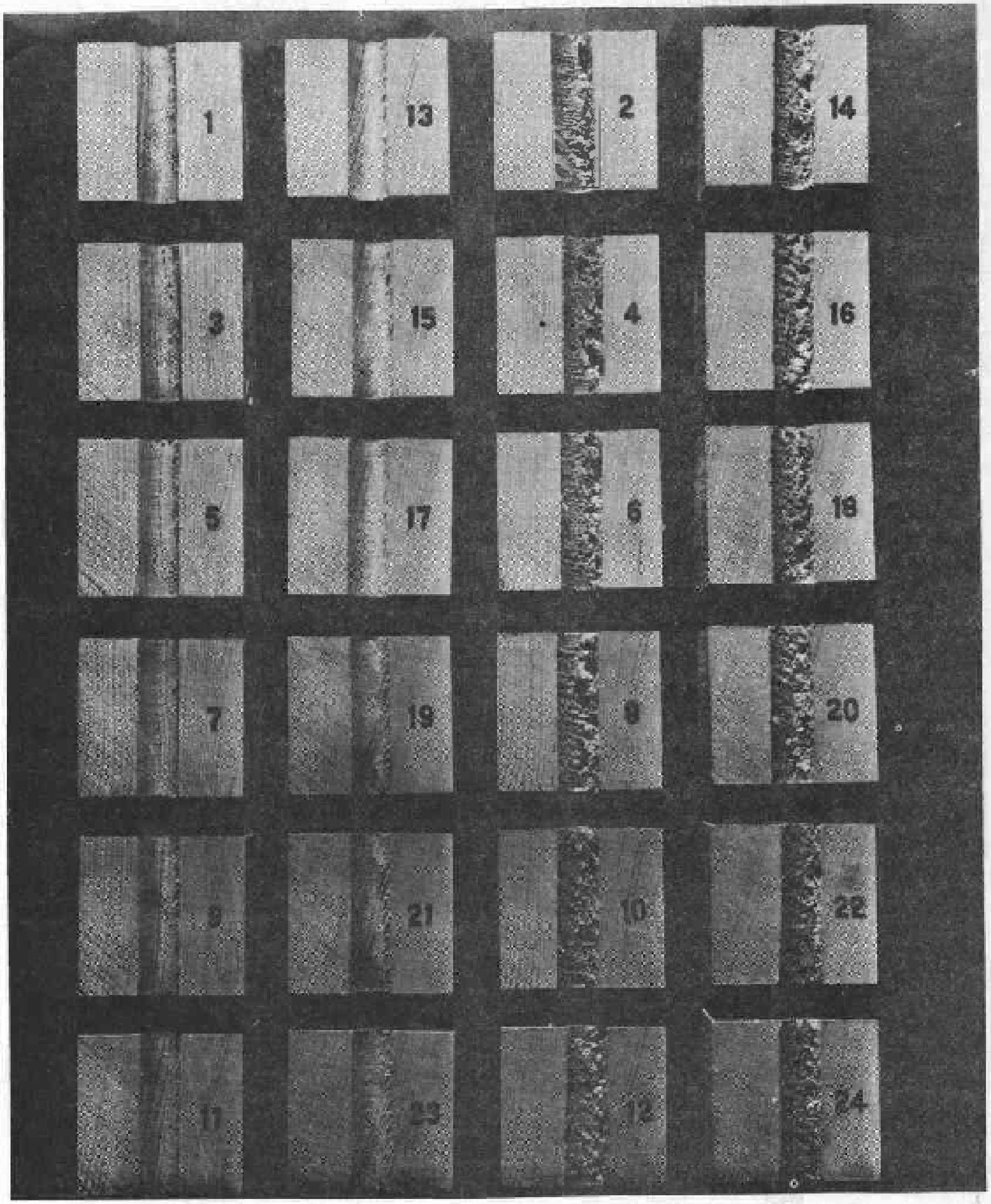

Figure 8.--Effect of rate of feed on smoothness of 1/2-inch hole drilled with a twist drill in Sitka spruce. Two rows of smoothly drilled blocks at left drilled at 800 revolutions per minute with a feed of 2 inches per minute (series 5, table 1); two rows at right drilled at 200 revolutions per minute with a feed of 60 inches per minute (series 6, table 1).

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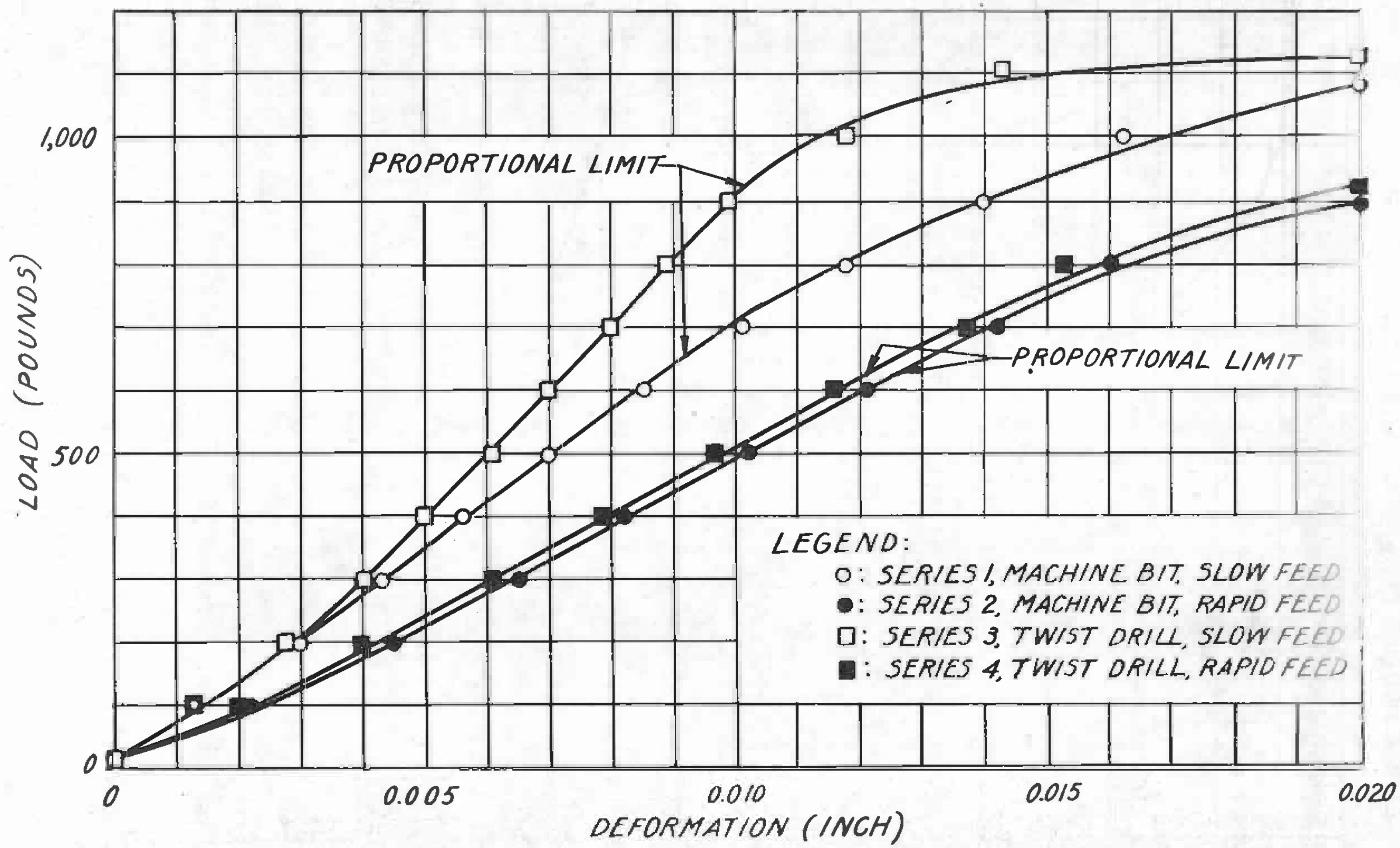

Figure 9.--Composite load-deformation curves for bolt-bearing tests using 1/4-inch steel aircraft bolts on 65-35, seven-ply, 3/4-inch Douglas-fir plywood, showing effect of type of drill and rate of feed. Each curve represents 5 specimens.

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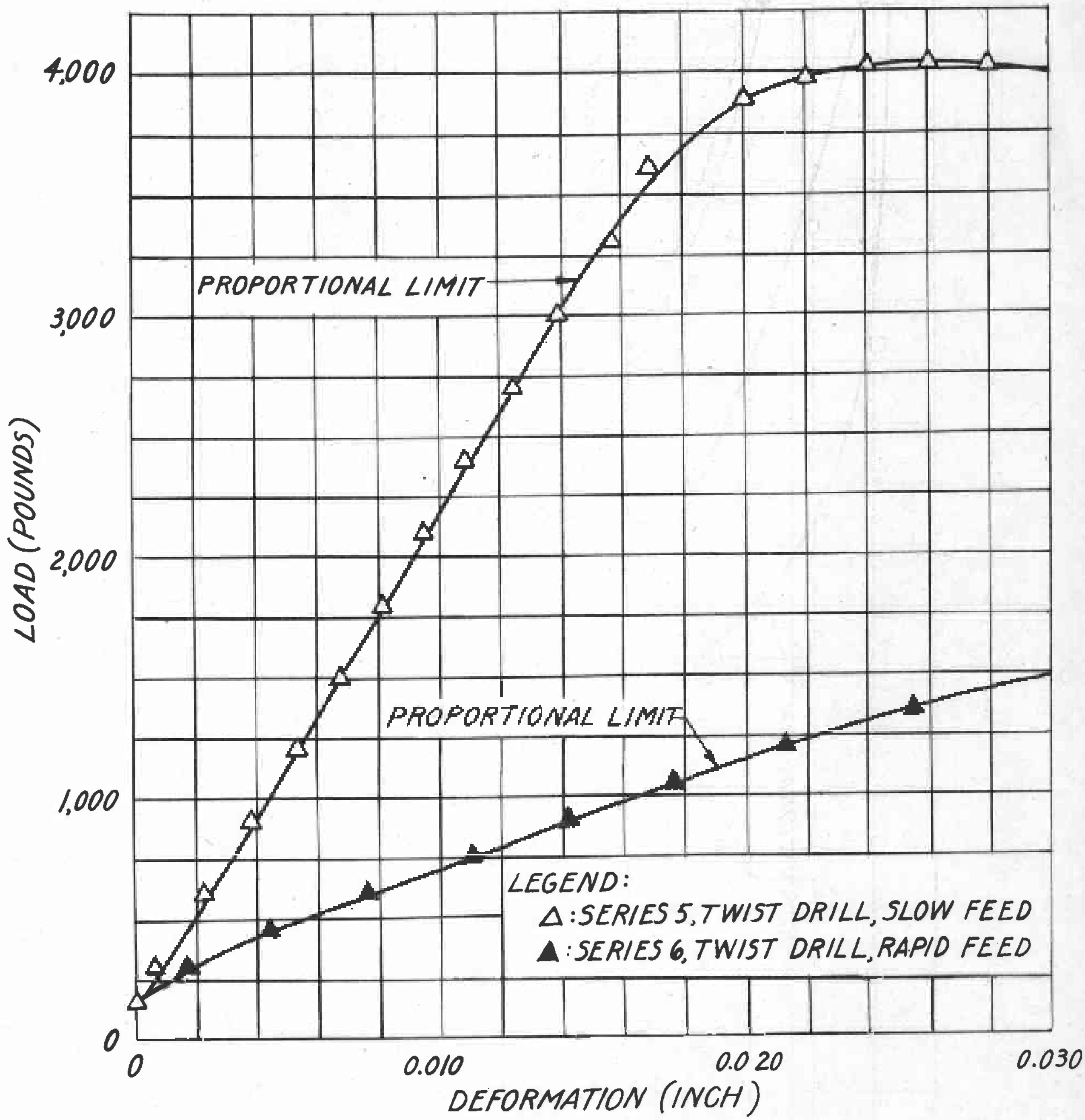

Figure 10.--Composite load-deformation curves for bolt-bearing tests using 1/2-inch steel aircraft bolts on 2-inch Sitka spruce, showing effect of rate of feed. Each curve represents 13 specimens.

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