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Building Research Association
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TWO-NAIL VERSUS SINGLE-NAIL JOINTS OF NEW ZEALAND-GROWN PINE

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Introduction: R. S. Whitney graduated with a Bachelor of Science in Industrial Chemistry at the University of Wales Institute of Science and Technology during 1968. He received his Ph. D. at the University of Essex during 1971. Subsequently, he was awarded a Royal Society European Fellowship for post-doctoral studies at the University of Freiburg, Federal Republic of Germany. During 1972, he moved to New Zealand and joined the Building Research Association of New Zealand, where he investigated the strength of wood joints, the wood-drying rates, the stability of wood-framed houses, and the corrosion of metals in contact with wood. During 1976, he was appointed the Head of the Materials Research Division of BRANZ, being involved in studies of the durability and serviceability of exterior-grade wood-based products and the effects of weathering on urea-formaldehyde flooring-grade particleboard after its installation in the framed structure.

ABSTRACT

Static withdrawal tests were performed on 100 x 4.5 mm plain-shank framing nails in single and two-nail, green and seasoned, Corsican and radiata pine joints. Joints with nails driven into the side-grain of dry wood were stronger than those with nails driven into the side-grain of green wood, however, not quite as much as expected. Joints with nails driven into the end-grain were generally not weaker than joints with nails driven into the side-grain. Toe-nailing produced stronger joints than straight nailing. Single-nail joints do not necessarily predict the performance of two-nail joints, if the nails are tested for their withdrawal resistance. Delayed nail-withdrawal resistance is not correlated to immediate nail-withdrawal resistance.

Information on the strength and performance of nailed joints is particularly important in New Zealand. The majority of dwellings are single-unit wood-framed houses, and New Zealand is prone to relatively high seismic activity and frequent high winds. For example, in Wellington, the second largest population center, the design wind speed, based on the 50-yr. return period for a 3-sec. gust, is 51 m/s (114 mph), with wind gusts of 27 m/s (60 mph) or more occurring at an average of 41.5 days each year. In addition, there is a return period of 20 years for earthquakes of intensity VII on the Modified Mercalli scale.

In New Zealand the main wood species used for house framing is radiata pine (Monterey pine). Generally the wood is preservative treated (normally with boric salts) and used while green. Fasteners in most of the structurally significant joints are normally 100mm (4")-long common wire nails of either 4 or 4.5mm diameter. Wall structures have traditionally been made of 50 by 100 mm (2x4) studs, 450 mm (18") on centers, with up to three rows of bracing. The new building regulations (DZ3604) allow, however, a greater variety of stud sizes and spacings. Wall framing is rarely sheathed with plywood, as is normal in the USA. Wall siding, such as wood siding, asbestos siding or masonry, are attached directly to the framing, with the bracing provided by diagonal wood or steel members, and the plasterboard wall paneling. Conventional rafter roof framing is still more common than are trussed rafters; but the latter are becoming increasingly popular.

Most of the previous studies of the withdrawal resistance of nails (e.g., Hellawell, 1961; Mack, 1960; and Stern, 1969) were carried out with single nails; however, most joints in the wood-framed houses contain pairs of nails. Therefore, in the present study, two-nail joints were tested which are typical of those found in wood house frames. For reasons of comparison, some of the tests were repeated using single-nail joints.

Three main types of joints were investigated:

1) Joints nailed straight into the side grain, modeled after the purlin/rafter joint (Fig. 1).
2) Joints nailed straight into the end grain, as in the plate/stud joint (Fig. 2).
3) Toe-nailed joints also known as skew-nailed or slant-nailed joints, as in the rafter or ceiling-joist/top-plate joint (Fig. 3).

Joints were assembled with both green (wet) and seasoned (dry) boric-treated radiata pine, using 100 x 4.5 mm common wire brads. These nails were of the same length as, but slightly thinner than 20d nails. The nails had medium diamond points.

Some of the tests were repeated using a second species, Corsican pine, which is the major other pine species used in New Zealand. In design codes, this species is generally grouped with radiata pine and is often sold as such.

The changes that can occur in the performance of nailed joints subsequent to nailing are well known (e.g., Hellawell, 1961 and 1967; Mack, 1960; and Stern, 1969). For this reason, the testing of the major portion of the joints tested during this study was delayed. The delay was sufficiently long for the green-wood joints to reach an equilibrium moisture content and for the moisture content of the dry joints to change with the different laboratory conditions. For reasons of comparison, two groups of joints were tested immediately (within 15 min.) after assembly.

Nails were driven with a hand-hammer using nailing jigs to locate the nails. Nails for the single-nail withdrawal tests were driven into the edge or end of 100 x 50 mm pieces. Single-nail penetrations (57mm/nail) into the nailing members were the same as the two-nail penetrations.

The joints were tested for separation resistance in the direction of the nail axis with a Hounsfield tensometer which was accurate to ± 2%. Load-slip curves were recorded and the maximum load, that is, the ultimate resistance to withdrawal was observed.

The results are summarized in Table I. Analyses of variance were carried out to assess the effects of the variables (moisture content, delay, number of nails, etc.) on the performance of the joints. The results of these analyses are summarized in this paper, with the full details given in the original reports.

1) Density and Species

Six lots of lumber were used for tests. The results, corrected for variations in the density of the six lots, are shown in Table II. These results were corrected to an oven-dry density of 0.44. This is equivalent to a density of 0.42 based on oven-dry weight and volume at 12% moisture content. The corrections were made according to the empirical formula given in the Wood Handbook (U. S. Forest Products Laboratory, 1974), $P = 0.054\ G^{2.5}DL$, where P is the withdrawal resistance of bright common wire nails driven into the side grain of dry wood, or unseasoned wood that remains wet; L is the depth of penetration; and D is the nail diameter.

A comparison of the corrected strength of the two-nail joints in Corsican pine (lot 6) with similar joints in radiata pine (lots 4 and 5) indicated no significant differences between the species, other than those accounted for by the different densities of the lots.

2) Delay Prior to Testing

The effects of delays on the withdrawal resistance of the nails in side-grain wood are shown in Fig. 4. The large decrease in performance that occurs during seasoning of the wet joints confirms the well-known phenomenon that the withdrawal resistance of nails from the side grain of green wood drops as the wood seasons.

A decrease in the delayed performance of the nails driven into the side grain of dry wood is also indicated in Fig. 4. This decrease occurred even when the testing was delayed as little as one to two weeks. This effect apparently contradicts some of the findings of Hellawell, 1961; Mack, 1960; and Stern, 1969. Hellawell, however, found that a decrease in strength occurred with nails driven into wood which had been kiln-dried to 21%, when the moisture content decreased an additional 5% during the delay prior to testing. He suggested later (1967) that this decrease in strength is associated with a change in moisture content rather than as a result of delays in testing and that it may occur with dry wood if its moisture content changes after nailing. In the present study, the dry joints were stored in a laboratory climate which was not closely controlled. Consequently, changes in the moisture content of the dry joints were likely to have occurred prior to testing.

These results highlight the importance of the delayed testing of nails in withdrawal from both green and dry-nailed joints. They also indicate that it is necessary for nails driven into dry wood,to induce a change in moisture content similar in magnitude to that which might occur in practice. In framed residential structures, the immediate resistance to withdrawal is of little significance. Therefore, only the delayed test results were given consideration in the following analysis of the findings.

3) Number of Nails

Earlier studies of the withdrawal resistance of nails were carried out with single nails driven into wood. Recommended procedures for testing nails (AS 1649, 1974; ASTM 1761, 1974) involve the determinating of the withdrawal resistance of single nails at a time. Design calculations for the withdrawal resistance of nails in joints using two (or more) nails are made under the assumption that design load = single nail design load x number of nails.

For the joints assembled with green wood and tested during this study, this assumption holds, since the strength of two-nail joints is at least twice that of single-nail joints (Table II). For the dry joints, however, the above assumption is not correct, since the strength of two-nail joints is considerably less than twice that of single-nail joints. This is shown graphically in Fig. 6, in which the withdrawal resistance per nail is plotted against the number of nails in the joint. When the assumption holds, the slope of the graph is horizontal. The discrepancy is greater for nails driven into the side grain of dry wood, a condition often used as a reference from which the strength is deduced for other conditions.

The withdrawal resistance of nails driven into the side grain of dry wood can be predicted from the U. S. Forest Products Laboratory equation as being 1.6 kN for single nails and 3.2 kN for two nails in a joint. While the value for the single-nail withdrawal resistance is in good agreement with the value calculated from the empirical equation (Table II), this equation is not applicable to two-nail joints tested after a delay subsequent to their assembly.

It is possible that these divergences may be peculiar to the relatively small nail spacings (10 nail diameters) used in this study. Yet, the result is of significance when considering the structural performance of wood-framed houses which contain many two-nail joints of the types investigated.

Therefore, the single-nail resistance to withdrawal is considered in this paper only to highlight the dangers of applying the above assumption to two-nail joints in wood-framed houses.

4) Moisture Content of Wood

It has generally been recognized that driving common wire nails into green wood results in considerably weaker joints after the wood has seasoned than nailing into dry wood. For example, Stern reported delayed single-nail withdrawal resistance values for nails driven into the side grain of green southern pine, which amounted to only 38% of the comparable values for nails driven into dry wood. Mack, 1960 reported similar differences. A decrease up to 45% occurred during this study (Table II), however, only for delayed single-nail withdrawal from side-grain wood.

This large decrease in the delayed single-nail withdrawal resistance of nails from green as opposed to dry wood was not observed for any of the other tested combinations of factors (Fig. 7). The delayed withdrawal resistance of the green side-grain two-nail joints was, on the average, 83% of the comparable value for dry wood. For single nails driven into the end grain, this decrease was only to 70% of the dry value. For the end-grain two-nail joint, there was no significant difference in performance for joints assembled with green and dry wood. With toe-nailed joints, the opposite trend was noted, that is, the joints assembled with green wood were considerably stronger than those assembled with dry wood.

5) Direction of Grain of Wood

One of the potentially most controversial aspects of the test results is the performance of joints with nails driven into the end grain versus the side grain of the tested wood (Table II and Fig. 8). The strength of end-grain two nail joints was not affected by the moisture content of the wood. End-grain joints provided a significantly higher delayed withdrawal resistance than similar side-grain joints assembled with green wood. On the whole, the end-grain joints were not significantly weaker than the side-grain joints assembled with dry wood.

Stern, 1969 and Hellawell, 1961 (Table III) found that nails driven into end grain were much less affected by delays in testing than nails driven into side grain. When tested immediately after nailing, nails in end grain had inferior holding properties to nails in side grain; however, when tested after a delay, there were no overall differences. In their work as well as in the present study of single-nail joints, the delayed resistance to withdrawal from end grain of wet wood was at least as good as, if not better than, comparable values for nails in side grain. Although the resistance to withdrawal from the end grain of dry wood was not as high that from the side grain of dry wood, it was, on the average, as high as that from the side grain of wet wood.

Although the presented results are not at variance with previous research, it is necessary to give consideration to why end-grain joints have been regarded as having little strength. Is it a misapplication of research data? Possibly, reduction factors, for example, for green wood or delayed withdrawal, which were derived from side-grain nail-withdrawal tests, were incorrectly applied to the immediate nail withdrawal resistance from end-grain wood. Another factor could, of course, be the rather poor performance of two-nail joints as opposed to single-nail side-grain joints, since this did not occur in end-grain joints.

The poor reputation of end-grain joints could also be the result of a misconception which was arrived at by carpenters on the basis of their own experience with nail withdrawal, since this experience is normally based on withdrawing misdriven nails immediately after driving.

Alternatively, are nails in end-grain wood unreliable in practice and are, therefore, our test data unrepresentative? Perhaps the static withdrawal tests do, for example, not represent actual stress conditions; or end-grain joints are perhaps more susceptible than side-grain joints to deterioration caused by cyclic strains which occur during the life of the joints. The author would appreciate comments on this aspect of the paper.

6) Toe-Nailing

The results (Table III and Fig. 9) indicate considerable increases in resistance to withdrawal if joints are toe-nailed rather than straight-nailed. This improvement is larger for green-wood joints than for dry wood joints. These findings should be treated with caution, because the increase in ultimate withdrawal resistance was not accompanied by an equivalent decrease in withdrawal slip, since the ultimate loads generally occurred at greater slips (Fig. 5). In addition, the performance of toe-nailed joints is susceptible to variations in depth of nail penetration due to either a variation in the angle in which the nail is driven or its distance from the edge of the nailed member.

Yet, according to the data presented, stronger joints may be obtained by toe-nailing in situations where withdrawal forces exerted on nails are critical. One such application is the purlin/rafter joint, where failures due to wind uplift forces could occur.

Conclusions

Joints with nails driven into the side grain of dry wood were stronger than joints with nails driven into the side grain of green wood; however, not as strong as predicted from single-nail withdrawal tests or the generally accepted empirical equation. Joints with nails driven into the end grain of both green and dry wood were not significantly weaker than joints with nails driven into the side grain of dry wood; however, they were stronger than the joints with nails driven into the side grain of green wood. Toe-nailing into the side grain resulted in stronger joints than straight-nailing either into the side grain or into the end grain, with the toe-nailed joints assembled with green wood being stronger than those assembled with dry wood. The tests also indicated that, while toe-nailed joints were stronger than straight-nailed joints, they were not necessarily stiffer, with the ultimate test loads being developed at larger displacements.

The weakest type of nailing, that is, straight-nailing into the side grain of green wood, is commonly used for purlin/rafter joints in house construction in New Zealand. This is a joint which is prone to failure in storms. It could easily be strengthened by the use of dry wood or preferably by toe-nailing.

Delayed nail-withdrawal resistance is not related by any constant factor to immediate nail-withdrawal resistance. Misleading results may, therefore, be obtained by testing immediately after nailing.

Single-nail withdrawal tests do not necessarily predict the behavior of two-nail joints. Tests should be carried out on such joints as are used in practice.

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Editor's Note: Subsequent to the presentation of this paper, the following discussion took place:

1) Relaxation of the compressed wood fibers around the shank and the point of a driven fastener causes its immediate withdrawal resistance to decrease during delayed testing, especially when the moisture content of the wood has decreased.

2) In two-nail joints, that nail fails first in withdrawal which is driven into the weaker location in the wood, such as into a soft annual springwood ring. When this happens, the second nail becomes overloaded, which causes the joint to fail. Consequently, failure of a two-nail joint can be expected to occur at a relatively low joint load. In contrast, failure of a single-nail joint usually happens only when the nail reaches its ultimate withdrawal resistance. Thus, the average nail withdrawal-resistance value for single-nail joints should be higher than that for two-nail joints. Since variability in wood properties is given full consideration when arriving at design values for driven fasteners, either the single-nail joint should be the basis for design-value derivation or the variability factor should be decreased if the two-nail joint is the basis for design-value derivation.

3) As indicated by the author, the depth of penetration of a toe-nailed fastener into the nailing member depends on (a) the end-distance of the fastener, measured along the face of the nailed member, and (b) the angle of driving. According to Fig. 3, the toe-nailed fasteners were driven at an angle of 45° during this study, whereas it is customary to toe-nail at an angle of approximately 30° to the vertical. The latter nailing procedure increases the depth of penetration into the nailing member; however, decreases the wood-shear area, hence, the wood-shear resistance at the end of the nailed member. This variation in toe-nailing may explain the discrepancy in withdrawal-resistance values for straight and toe-nailed fasteners observed during this and previous studies.

Table I. Experimental Design and Summary of Results, Including 95% Confidence Limits

Type of Joint:			Side-Grain				End-Grain		Toe-Nailed	
Moisture Content When Nailed:			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Tested:			Immediately		After Delay		After Delay		After Delay	
Lot	Joint	Density	Average Ultimate Withdrawal-Resistance (KN)							
1 N=12	Radiata 2 Nails	430	3.17 ±.43		1.42 ±.19					
2 N=12	Radiata 2 Nails	470		3.68 ±.50		1.69 ±.23				
3 N=27	Radiata 2 Nails	450			2.13 ±.18	1.75 ±.14				
4 N=27	Radiata 2 Nails	440					2.19 ±.16	2.15 ±.16		
5 N=27	Radiata 2 Nails	440							2.97 ±.13	3.94 ±.17
6 N=20	Corsican 2 Nails	420			2.16 ±.23	1.46 ±.16	1.81 ±.20	1.88 ±.20		
6 N=20	Corsican 1 Nail	420			1.57 ±.17	0.71 ±.08	1.11 ±.12	0.78 ±.08		

N= Number of Replicates. Density of wood in KG/M^3.

Table II.- Withdrawal Resistance, Corrected for Different Wood Densities

Type of Joint:			Side				End		Skew	
Moisture Content When Nailed:			Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Tested:			Immediately		After Delay		After Delay		After Delay	
Lot	Joint	Density	Average Ultimate Withdrawal Resistance (KN)							
1 N=12	Radiata 2 Nails	430	3.34		1.50					
2 N=12	Radiata 2 Nails	470		3.12		1.43				
3 N=27	Radiata	450			2.08	1.71				
4 N=27	Radiata 2 Nails	440					2.19	2.15		
5 N=27	Radiata 2 Nails	440							2.97	3.94
6 N=20	Corsican 2 Nails	420			2.43	1.64	2.03	2.11		
6 N=20	Corsican 1 Nail	420			1.76	0.80	1.25	0.88		

Values are Corrected for Density of 440 KG/M^3 (G = 0.44) According to Equation: $P = 0.054\ G^2\ DL$.

Table III.- Comparison of Withdrawal Resistance From End-Grain and Side-Grain Wood

Tested:		Immediately				After Delay			
Moisture Content When Nailed:		Dry		Wet		Dry		Wet	
Direction of Grain:		Side	End	Side	End	Side	End	Side	End
Source	Nail Penetr. (MM)	Withdrawal Resistance (KN)							
Hellawell (1961): Radiata Pine	32x2.6	0.57	0.39	0.76	0.40	0.61	0.40	0.51	0.51
Stern (1969): Southern Pine	51x4.1	2.01		2.48	1.21	1.92		0.73	0.72
	51x3.5	1.57		1.95	1.02	1.37		0.56	0.68
Whitney (1977):									
- Corsican Pine With One Nail	57x4.5					1.76	1.25	0.80	0.88
- Corsican Pine With Two Nails	114x4.5					2.43	2.03	1.64	2.11
- Radiata Pine With Two Nails	114x4.5					2.08	2.19	1.71	2.15

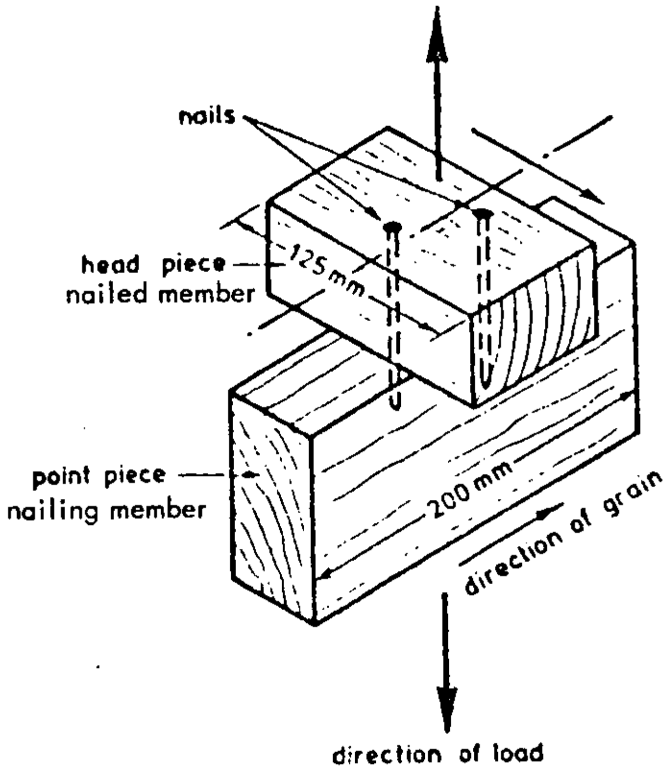

Fig. 1.- Straight-nailed into side grain: Purlin/rafter joint.

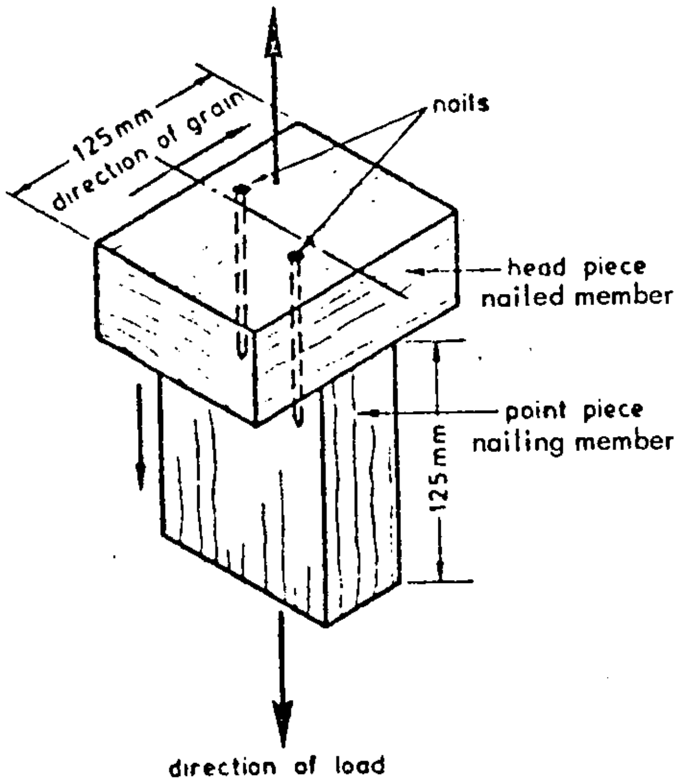

Fig. 2.- Straight-nailed into end grain: Plate/stud joint.

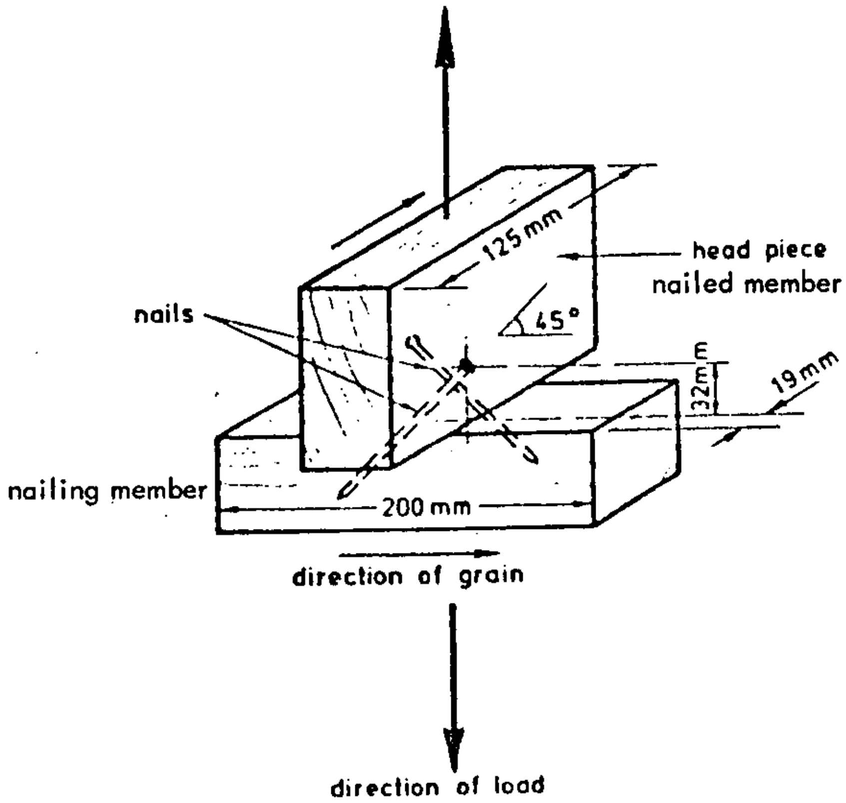

Fig. 3.- Toe-nailed into side grain: Joist/ top-plate joint.

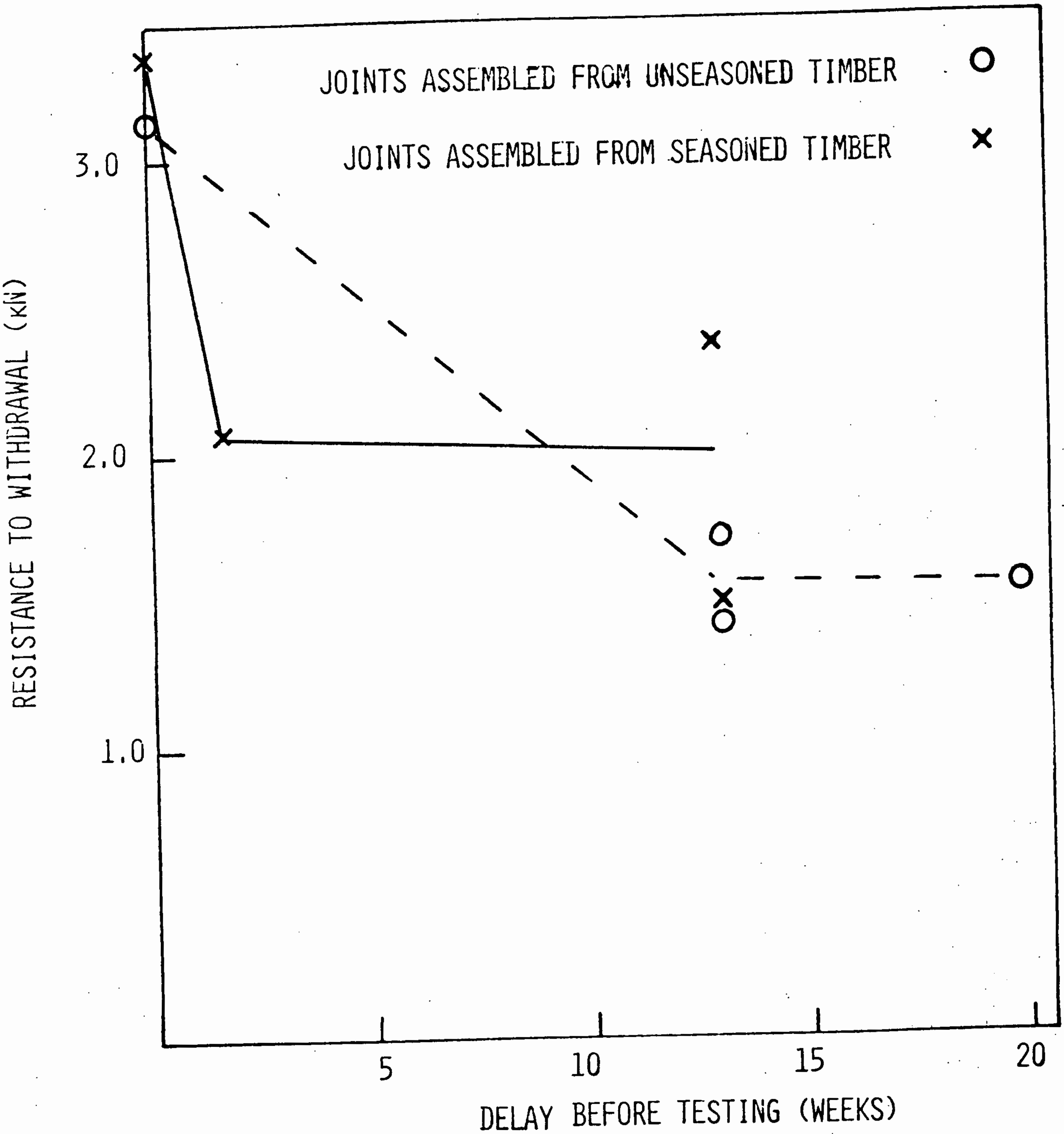

Fig. 4.- Effects of delay in testing on nail-withdrawal resistance.

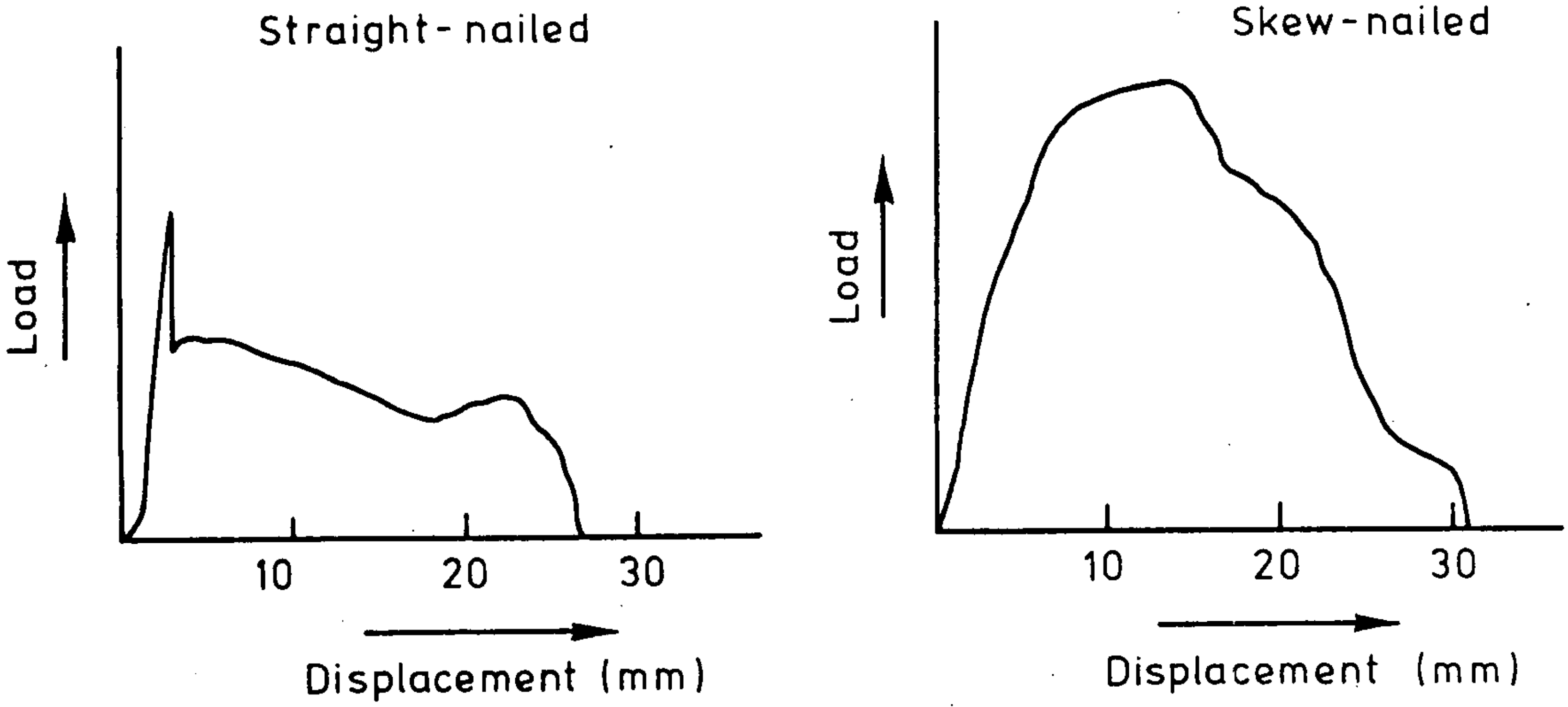

Fig. 5.- Typical load-deformation curves for straight-nailed and toe-nailed joints. The diagrams are tensometer traces and include deformations resulting from joint adjustments and wood compression.

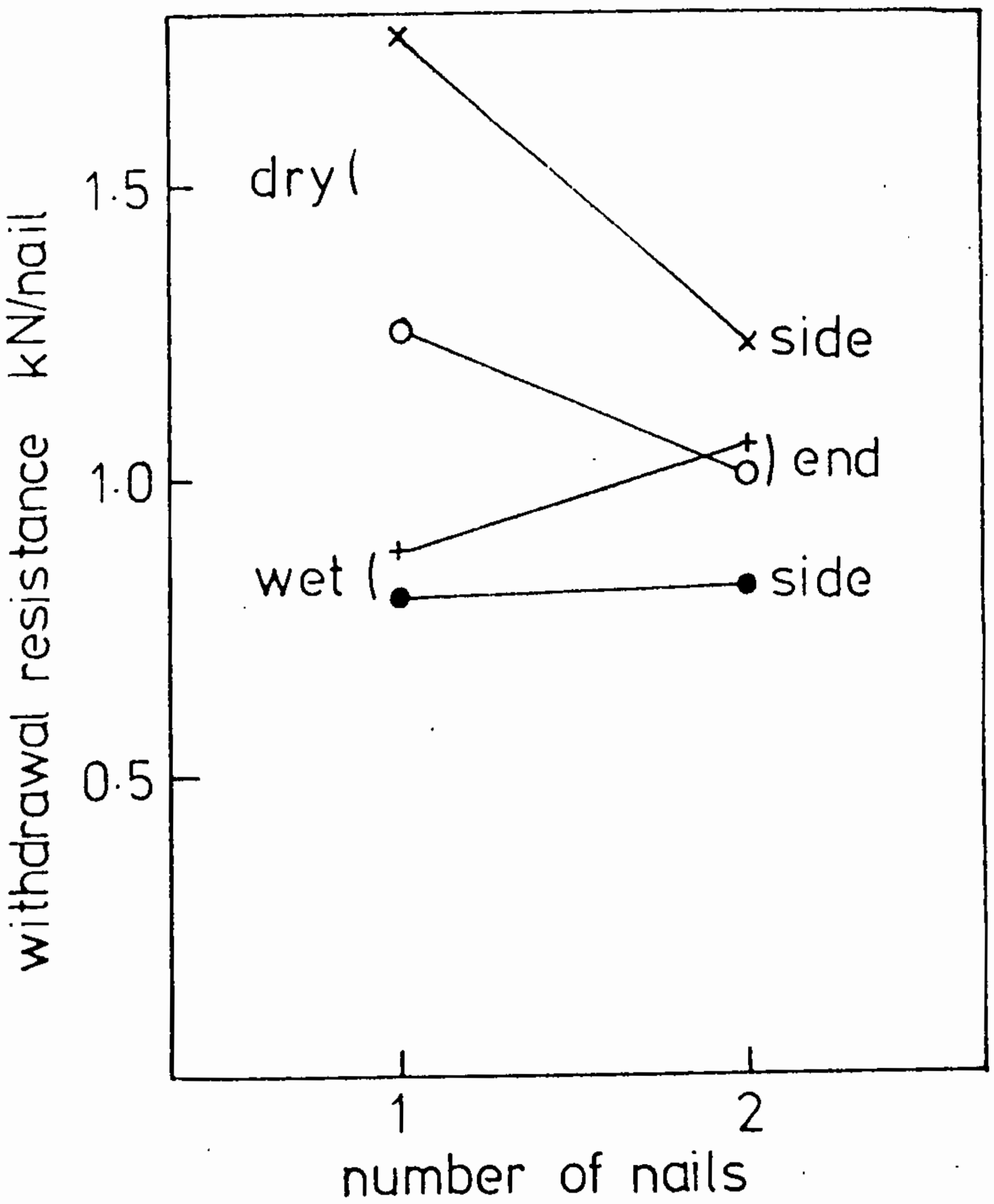

Fig. 6.- Variation in strength of joint with number of nails in joint.

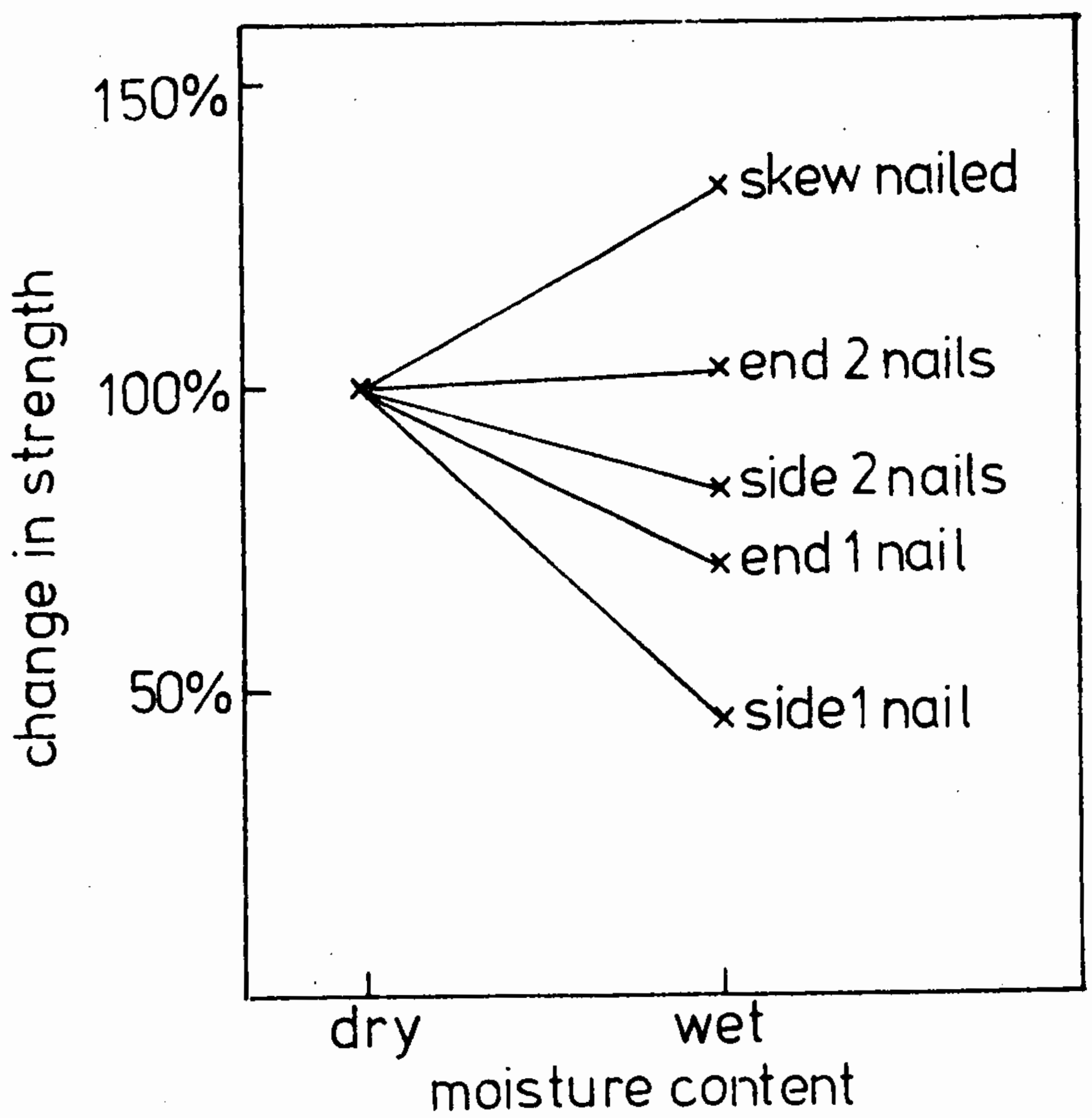

Fig. 7.- Variation in strength of joint with moisture content of wood during nailing.

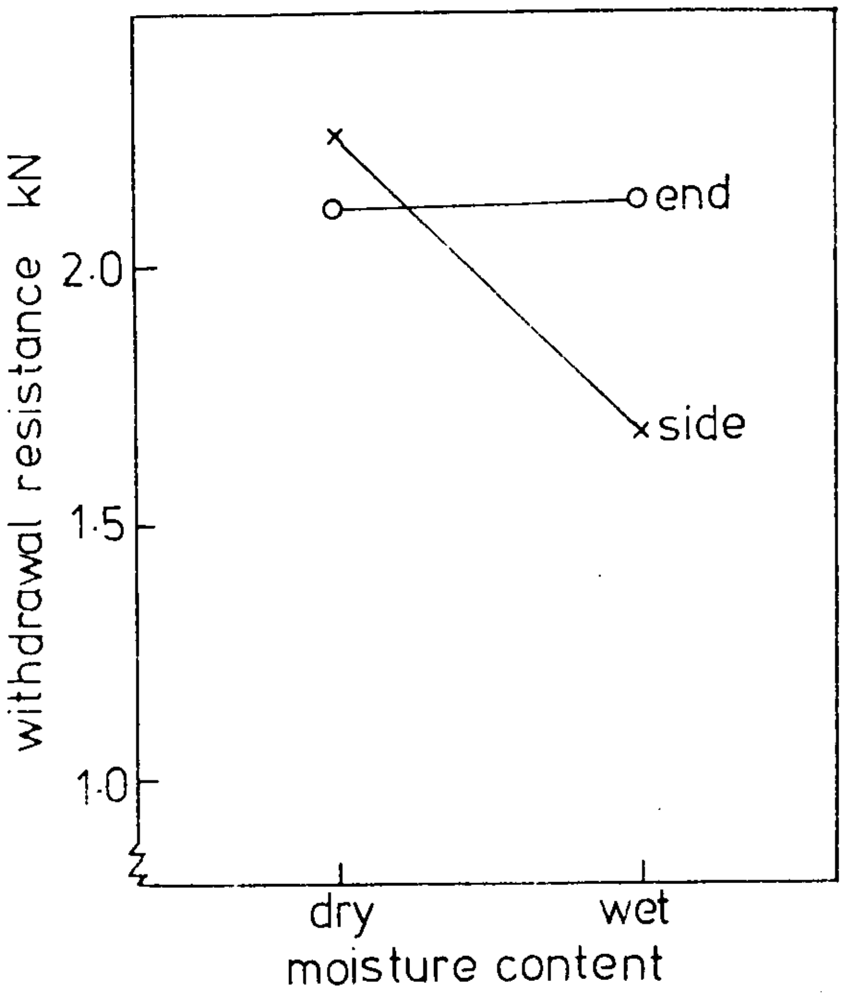

Fig. 8.- Variation in strength of joint with direction of grain of wood.

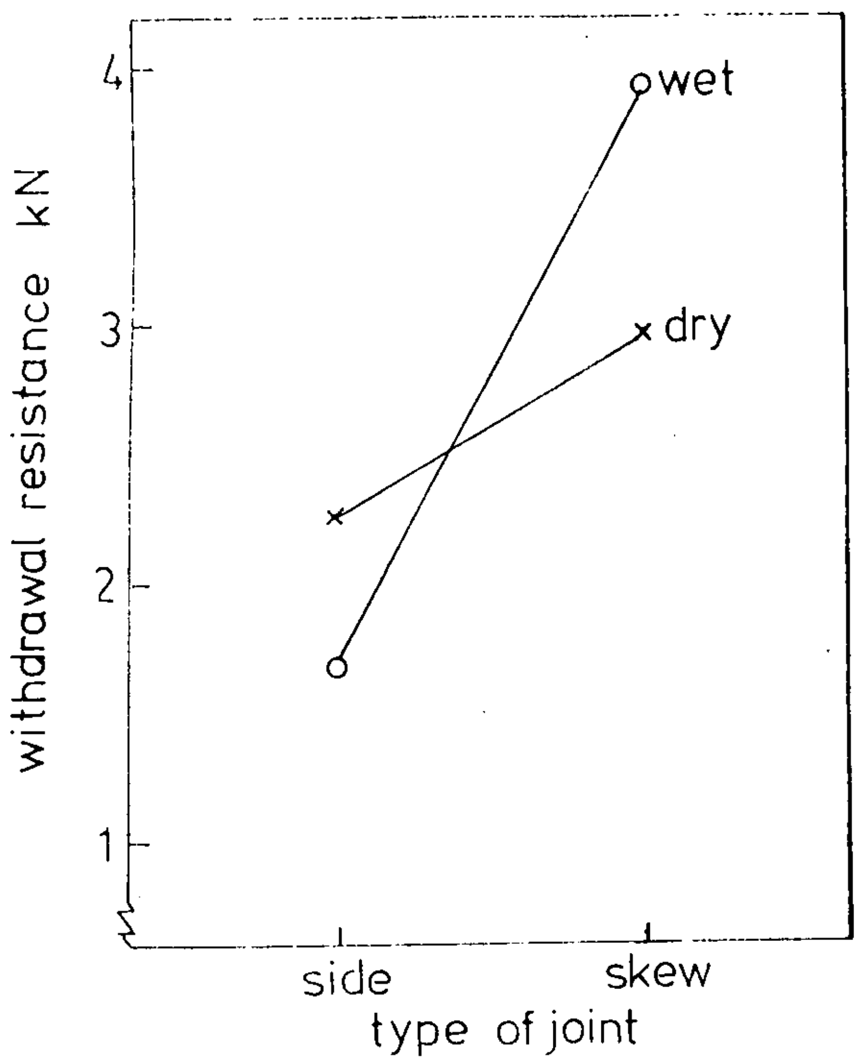

Fig. 9.- Variation in strength of joint with method of nailing.