Studies on Static Withdrawal Resistance of Nail*

—Effect of Driving Method and Time after Driving—

Wood Physics Section 3

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1 Introduction

On nailing many a study was made of various factors separately. The present report treats of many factors synthetically, never separately, under the same conditions and with the same materials.

Two experiments are described in this report. The major test was carried out to determine the difference, if any, in the withdrawal resistances of the nail driven by the static and the impact load. The sub-test was to investigate the variation of the static withdrawal resistance with time after driving. In both tests four experimental factors were considered: they were Wood Species, Nail Diameter, Driving Direction and Surface Coating of Nail.

2 Design of Experiment

The factors and their levels adopted in this experiment are shown in Table 1.

Table 1. Factors and Levels

Factor	Level		
A (Wood Species)	A_1 : SUGI	A_2 : HINOKI	A_3 : BUNA
B (Nail Diameter)	B_1 : 0.325 cm	B_2 : 0.414 cm	B_3 : 0.520 cm
C (Driving Direction)	C_1 : Longitudinal	C_2 : Radial	C_3 : Tangential
D (Nail Coating)	D_1 : Chromium	D_2 : Nickel	D_3 : Iron

Among these factors there are four main effects, six 2-factor interactions ($_4C_2$), four 3-factor interactions ($_4C_3$) and one 4-factor interaction ($_4C_4$). Since we do not as a general rule expect to get important results from 3-factor and higher interactions, in experiments with 4 or more factors, it is remarkable that so much

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of the experimentation effort is put into the determination of comparisons that are of no practical value. So two-factor interactions among A, B and C were considered and the interactions of D were not adopted, because they were assumed to be less effective on the withdrawal resistance of nails than the first three factors.

The factors A～D were arranged for the orthogonal array table $L_{27}(3^{13})$[1] so that four main effects and three 2-factor interactions (A×B, A×C, B×C) might be found, and the structure of the experiment is represented with a three split-plot design (in Table 2).

Table 2. Design of Experiment

A Combination of Levels (A～D)												……primary unit
M_1 (Static)						M_2 (Impact)						……secondary unit
K_1	K_2	K_3	K_4	K_5	K_6	K_1	K_2	K_3	K_4	K_5	K_6	……tertiary unit
—	—	—	—	—	—	—	—	—	—	—	—	
—	—	—	—	—	—	—	—	—	—	—	—	

Note : K_1, 1 hr after driving — K_4, 168 hr after driving
K_2, 5 〃 — K_5, 672 〃
K_3, 24 〃 — K_6, 3000 〃

3 Experimental Procedure

3.1 Wood Species

These tests were carried out with SUGI (Japanese ceder ; *Cryptomeria japonica* D. Don.), HINOKI (Japanese cypress ; *Chamaecyparis obtusa* Sieb. et Zucc.) and BUNA (beech ; *Fagus crenata* Blume). For each wood species nine 6 cm square by 30 cm long blocks were cut from a lumber and had been left in the air for about six months.

From driving till extraction test blocks had been left in a room with 10～20°C and 70～80% relative humidity.

3.2 Nail

Three sizes of nails were used: 2.5 SUN nail (about 7 cm long, 0.325 cm diameter), 3.5 SUN (10 cm, 0.414 cm) and 5 SUN (15 cm, 0.520 cm). For each size one hundred and eight nails were prepared and the angle of a nail point was ground to be 60°. One-third of the same size nails (i.e. 108÷3=36) was galvanized with chromium and another one-third was coated with nickel by means of ion exchange in order to prevent nails from rusting, but the rest was not treated for a control test to examine the effect of the surface treatment. All the nails were driven to a depth of 5 cm.

3.3 Driving Method

In the case of static driving an "Amsler" type testing machine was used and the rate of driving was about 1 cm/min (0.39 in/min). For impact driving the special apparatus shown in Fig. 1 was used and the hammer having 10.17 kg weight was repeatedly dropped on a nailhead from a height of 20 cm. When driving a nail, a support seen in Fig. 2 was used so that a nail might be driven perpendicular to a given face of specimens.

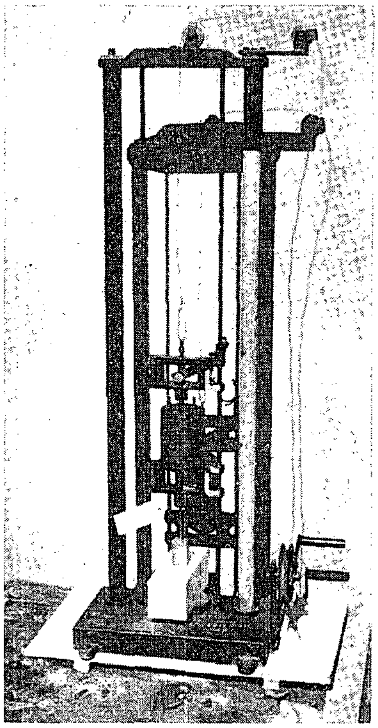


Fig. 1. The driving apparatus

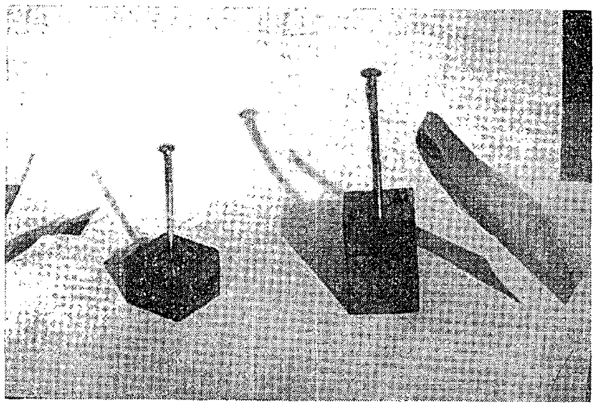


Fig. 2. Supports for driving nails

3.4 Withdrawal

Nails driven into blocks were pulled in random order 1, 5, 24 (1 day), 168 (1 week), 672 (4 weeks) and 3000 (about 4 months) hr after driving.

It was decided to represent the withdrawal resistance of nails by the largest load that was necessary to extract a nail from a given specimen. The extraction of nails was carried out by means of an "Amsler" type testing machine. The rate of withdrawal was about 1 cm/min (0.39 in/min), and during withdrawal the load required to extract a nail was continuously recorded on a drum attached to the machine.

4 Results and Discussion

The average results are shown in Tables 3~4 and Figs. 3~11.

4.1 Driving Method

The analysis signified that either the difference in the withdrawal resistances given by two driving methods or the effect of the interaction of driving method

Table 3. Table of Analysis of Variance

Factor	d.f.	S.S.	M.S.	ρ(%)
A	2	1757690	878845◎	51.5
B	2	342309	171155◎	9.9
C	2	246228	123114○	7.1
D	2	357259	178630◎	10.4
A×B	4	131825	32956	—
A×C	4	67603	16900	—
B×C	4	51780	12945	—
e_1	6	71104	11850	—
T″	26	3025798		
M	1	28472	28472◎	0.8
A×M	2	22620	11312◎	0.6
e_2	24	26909	1121	—
T′	27	3103799		
K	5	46916	9383◎	1.1
K×D	10	8137	814	—
e_3	255	234206	918	18.6
T	323	3383058		100.0

Note ◎ : significant at the 1 per cent level of probability
○ : significant at the 5 per cent level of probability
d.f. : degrees of freedom S.S. : sum of squares
M.S. : mean square ρ : contribution rate
e : error T : total variance

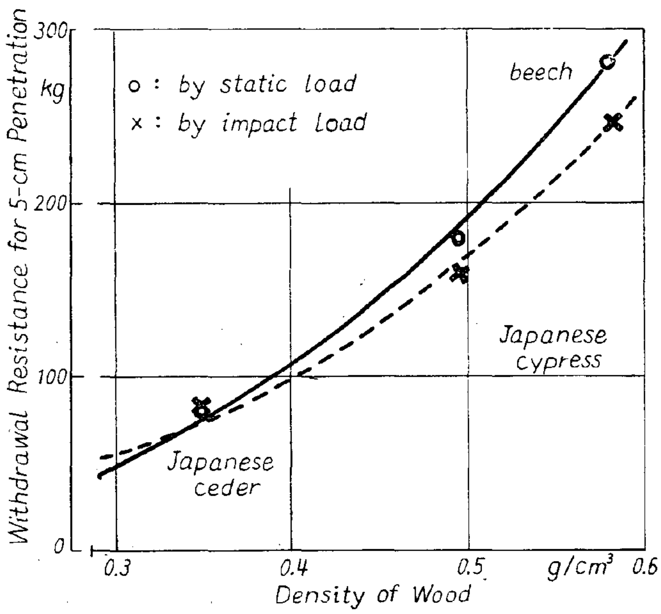
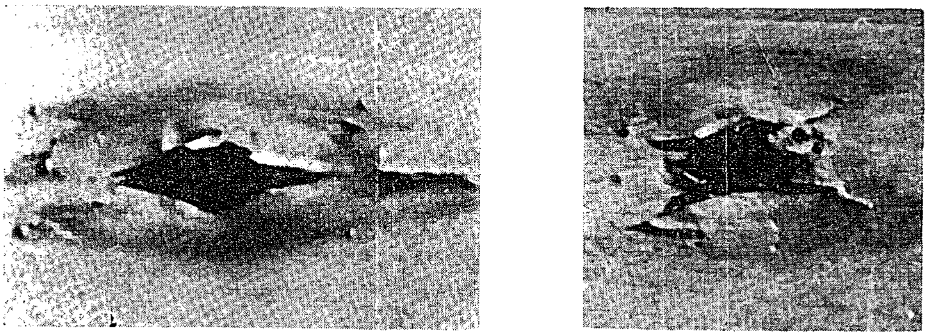


Fig. 3. Comparison between Withdrawal Resistance and Wood Species

and wood species (M×A) were significant at the 1 per cent level of probability. The average withdrawal resistance of the nail driven by the impact load was about 90 per cent of the value given by the static load (Figs. 3 and 5). The reason was investigated and it was found that the broken state of the wood structure, which is seen about the nail-hole given by the static load, differs from the one caused by the impact load (shown in Fig. 4).



Eig. 4. Pictures showing the broken states of the Wood structure.
Left : by static driving ; Right : by impact driving

In order to examine the influence of the broken state, $\Delta(=D-d)$ were read to the nearest 0.01 mm with a reading microscope 3~6 months after extraction, where Δ represents the amount of recovery (shrinkage) in the diameter of nail-holes ; D, the diameter of nails and d, the minor axis of nailholes (ref. Fig. 4), hereafter d is called the diameter of the nailhole, and in Fig. 5 the results are shown with broken lines. As seen in Fig. 5, the amount of recovery for the static load are always larger than that for the impact load.

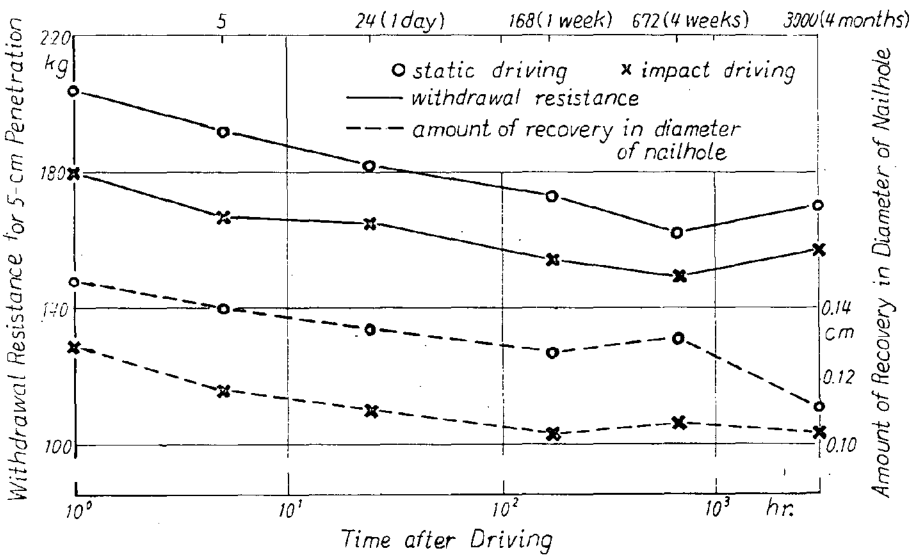


Fig. 5. Comparison between Withdrawal Resistances of Nails driven by static and impact driving

It can be considered that the withdrawal resistance is proportional to the pressure (p) exerting the shank of nails in the wood and that p is the force with which the compressed wood is restored to the former state. Considering that p is proportional to the amount of recovery in the diameter of nailholes, it may be remarked that the difference of broken states of wood is the cause for the significant differance in the withdrawal resistances of the nail driven by the static and the impact load.

For Japanese ceder, however, it was observed that there was no significant difference in the withdrawal resistances given by two driving methods ; more tests would probably have clarified the cause.

4.2 Time after Driving

The analysis of the results showed that the effect of time was significant at the 1 per cent level of probability. As shown in Fig. 5, the withdrawal resistance of nails decreases with time after driving till four weeks. This phenomenon can be explained, to a certain degree, by relaxation of stress.

Five mean values corresponding to time (1, 5, 24, 168 and 672 hr) after driving are shown in Fig. 6, and these five black points stand nearly in a line running

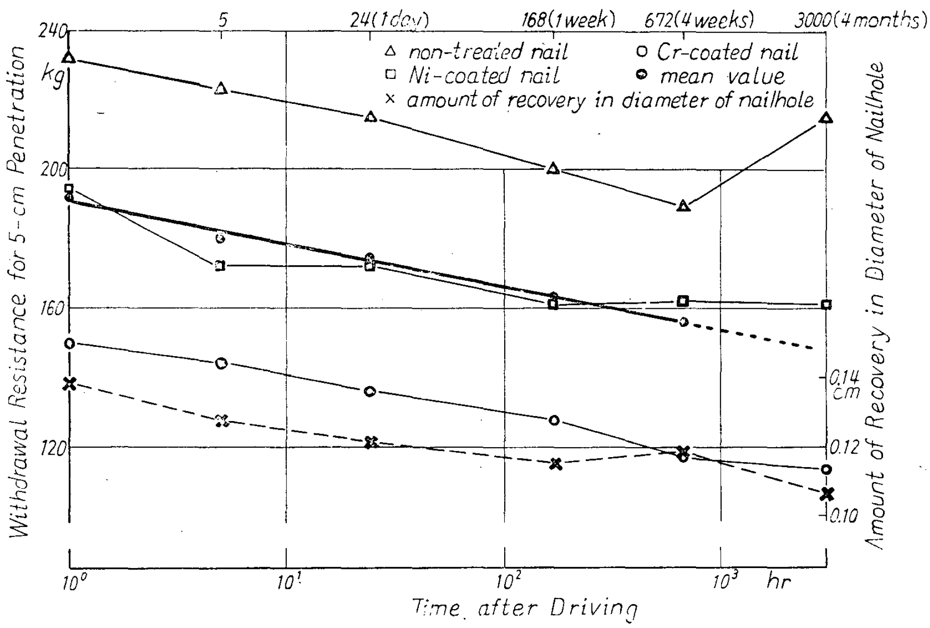


Fig. 6. Effect of Time after Driving on Withdrawal Resistance

parallel to the one showing the amount of recovery in the diameter of nailholes. These points being plotted on semi-logarithmic paper so that the effect of time might be estimated quantitatively, a straight line was obtained. Therefore, the relationship between the withdrawal resistance and time after driving can be given by the following formula :

$$P = a + b \log T \qquad (0 < T < 700 \text{ hr}) \qquad \cdots\cdots(1)$$

in which P represents the withdrawal resistance ; a and b, constants and T, time after driving, respectively. By the method of least squares a and b were determined as follows :

$$P = 191 - 12.6 \log T \quad (0 < T < 700 \text{ hr}) \qquad \cdots\cdots(2)$$

in which P represents the withdrawal resistance in kg for 5 cm penetration and T, time after driving in hr. The thick line in Fig. 6 was drawn from formula (2) and the slope of this line shows the general tendency between the withdrawal resistance and time after driving. This line runs approximately parallel to the line showing the amount of recovery in the diameter of nailholes. This phenomenon results from the fact that relaxation of stress increases with the lapse of time. Another equation should be considered beyond 700 hr.

4.3 Wood Species

As shown by many studies made of this factor, the withdrawal resistance varies remarkably with the wood species. In fact, the analysis indicated that the effect of the wood species was significant at the 1 per cent level of probability and that the wood species had the largest contribution rate to the total variance (ρ, $S'_A/S_T \times 100$; in Table 3), so it can be remarked that the very wood species is the factor having the most powerful influence on the withdrawal resistance of nails.

The effect of the wood species was highly significant and it can be conjectured that the cause consists in the strength, the structure and the contents of wood and that the strength, above all, has its powerful effect on the withdrawal resistance of nails. The density of the wood is the greatest factor that affects the strength of the wood. The relationship between the withdrawal resistance of nails and the density of the specimen being plotted on logarithmic scales, a line was obtained. Providing that only the density of the various wood species is the cause of the difference in the withdrawal resistance of nails driven into them, the following formula can be given :

$$P = cG^n + d \qquad \cdots\cdots\cdots(3)$$

in which P represents the withdrawal resistance ; G, the density of the specimen and c, d and n, constants, but d is assumed to be 0 empirically. By the method of least squares c and n were determined as follows :

$$\left.\begin{array}{ll} P = 1125\, G^{2.5} & \text{for static driving} \\ P = 937\, G^{2.3} & \text{fof impact driving} \end{array}\right\} \qquad \cdots\cdots\cdots(4)$$

in which P is represented in kg for 5 cm penetration ; G, in g/cm³. The curves in Fig. 3 were drawn on the basis of formula (4), however, these curves don't fit the measures very well. Considering that these curves should pass through the origin, they fit the measures pretty well.

4.4 Diameter of Nail

From the analysis the effect of the diameter of nails was significant at the

1 per cent level of probability. From Fig. 7 it is quite obvious that the withdrawal resistance is accurately proportional to the diameter of nails, so the withdrawal resistance can be given by the following formula within the range tested:

$$P = eD + f \quad \cdots\cdots(5)$$

in which P represents the withdrawal resistance; D, the diameter of nails and e and f, constants. In this case f can be assumed to be 0 empirically. By the method of least squares the following regression equation was obtained;

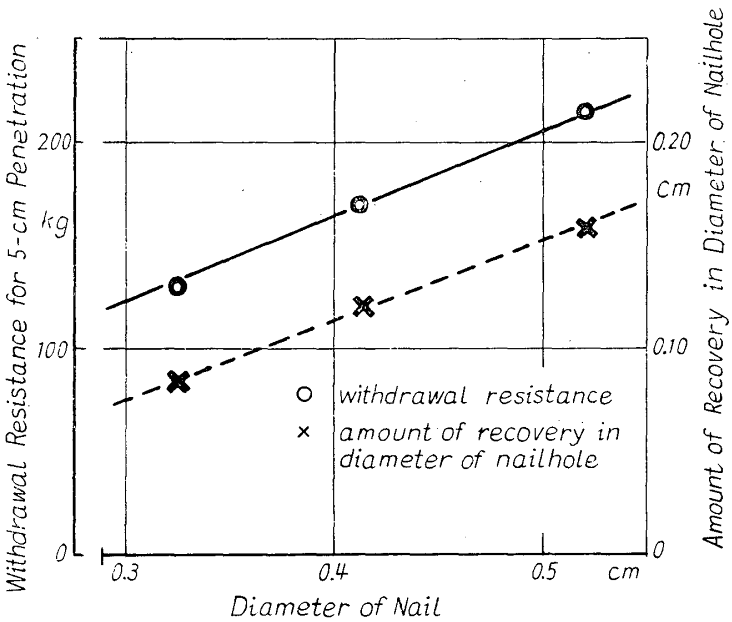


Fig. 7. Effect of Diameter of Nail on Withdrawal Resistance

$$P = 408\,D \quad \cdots\cdots\cdots\cdots\cdots\cdots(6)$$

in which P represents the withdrawal resistance in kg for 5 cm penetration and D, the diameter of nails in cm. The line in Fig. 7 was drawn from formula (6), and the broken line in the same figure shows the amount of recovery in the diameter of nailholes, it runs approximately parallel to the thick line.

4.5 Driving Direction

The analysis denoted that there was the 5 per cent level significant effect of the driving direction on the withdrawal resistance of nails.

It is easily assumed that for the nail driven in the longitudinal direction the withdrawal resistance is lowest. Which is higher the withdrawal resistance of the nail driven in the radial or the tangential direction? The data being closely analyzed, it was found that for beech and Japanese cypress the nail driven in the tangential direction showed the highest withdrawal resistance, however, in the case of Japanese ceder the result was contradictory (in Fig. 8).

At a certain depth the nail holding power could be analyzed as a problem on two-dimensional stress and orthotropic plane. Wood having plasticity as well as elasticity, this is not a simple problem which is easily analyzed mathematically. Apart from what a function of θ p is represented with, p' is given by the following formula[2]:

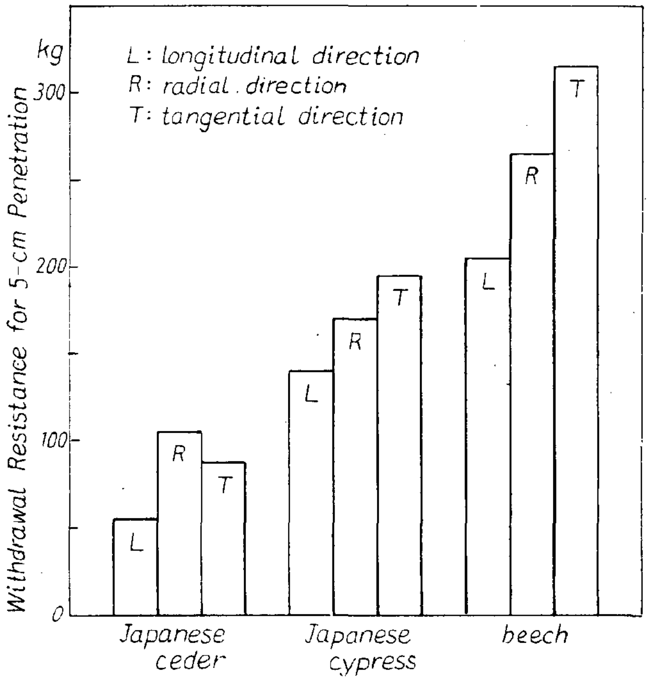


Fig. 8. Effect of Driving Direction on Withdrawal Resistance

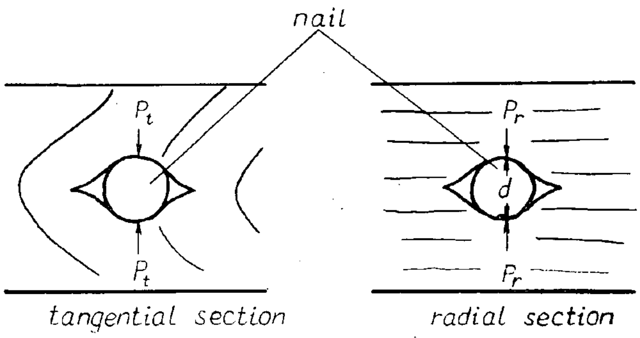


Fig. 9. The diagram of specimen-profiles p_t and p_r represent the nail holding power in the tangential and in the radial direction

$$p' = \frac{\int_0^{2\pi} p(\theta) d\theta}{2\pi}$$

in which p' represents an average nail holding power at a certain depth and θ, the direction angle of p. The shank of nails do not contact with wood uniformly. As previously mentioned, p' is highly influenced by the strength of the wood, so it might be considered that σ_t (the compression strength in the tangential direction) exerts deep influence upon the withdrawal resistance of the nail driven in the radial direction and σ_r (the compression strength in the radial direction) that of the nail driven in the tangential direction (in Fig. 9), provided that p' chiefly depends upon p in the direction perpendicular to fiber and that p is under the control of compression strength σ. From the results of the compression test (shown in Table 4), the following relationships were found :

Table 4. Physical Properties of Specimens

Wood Species	Density (g/cm³)	Compression Strength (kg/cm²)			Moisture Content (%)	Average Ring Width (mm)
		σ_l	σ_r	σ_t		
Japanese ceder	0.30~ **0.35** ~0.40	257~ **276** ~296	27~ **28** ~30	34~ **39** ~44	14.1~ **14.6** ~15.2	2.5~ **3.3** ~4.6
Japanese cypress	0.47~ **0.50** ~0.54	310~ **341** ~355	79~ **82** ~87	62~ **65** ~70	15.7~ **16.7** ~17.0	3.4~ **4.5** ~5.5
beech	0.56~ **0.58** ~0.60	405~ **437** ~474	128~ **130** ~133	74~ **77** ~79	12.6~ **13.1** ~13.3	1.5~ **1.8** ~2.4

$\sigma_r > \sigma_t$ for beech and Japanese cypress

$\sigma_r < \sigma_t$ for Japanese ceder

According to E. Gaber's study[3], it is most likely that for the wood species having σ_t over 60 kg/cm^2, $\sigma_r > \sigma_t$ is concluded and that for σ_t below 60 kg/cm^2, $\sigma_r < \sigma_t$. The reason why there was the significant effect of the driving direction on the withdrawal resistance of nails could be explained, if not the sole, by such relationships.

4.6 Surface Coating of Nail

The average results, either in the actual withdrawal resistance or in percentages of the value for the non-treated nail, are shown in Fig. 10.

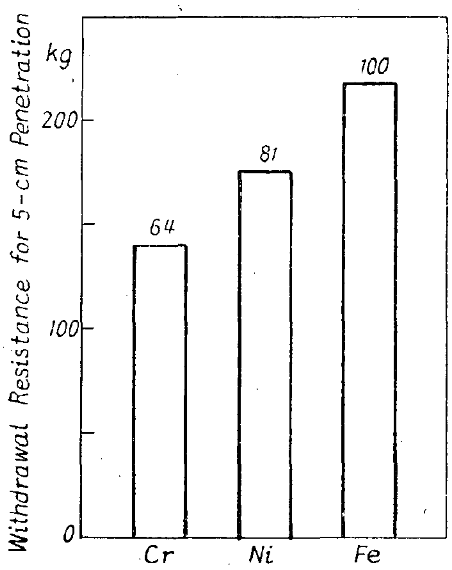


Fig. 10. Effect of Surface Coating on Withdrawal Resistance (Per Cent of Values for non-treated Nail)

Before the test it was presupposed that there was perhaps not so much effect of the surface treatment on the withdrawal resistance of nails. Being disappointed of the authors' expectations, the analysis indicated that the effect of the surface treatment was highly significant at the 1 per cent level of probability. It might be supposed that this phenomenon resulted from the difference in coefficient of friction between nails and wood. The effect of the surface treatment being segragated from the effect of time after driving, Fig. 5 was drawn. This figure shows that for the non-coated nail the withdrawal resistance decreases with the lapse of time after driving, but becomes curved upwards beyond four weeks, on the contrary, for the nail coated with chromium and nickel it keeps decreasing with time for four months. It is easily assumed that as for the non-coated nail rust of them makes the curve upward. But for rust, it could be remarked that the withdrawal resistance decreases as time after driving goes by.

4.7 Withdrawal Resistance and Energy required for Extraction

Although it is regarded as appropriate that the withdrawal resistance of nails is expressed by the energy required rather than by the highest load for extraction, it is very troublesome to determine the energy required to extract nails. As seen in Fig. 11 the energy is approximately proportional to the highest load required to extract nails, so it is little likely that the withdrawal resistance

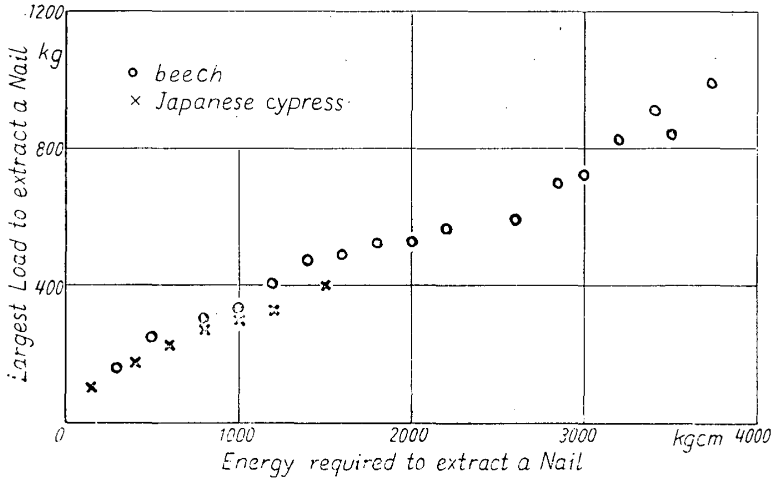


Fig. 11. Relationship between Energy and the Largest Load to extract a Nail

must not be expressed by the highest load to be easily measured.

4.8 Derivation of General Withdrawal Resistance Formula

On looking at Table 3, six main effects and an interaction effect are significant: they are A(wood species), B(diameter of nail), C(driving direction), D (surface coating of nail), M(driving method), K(time after driving) and $A \times M$ (interaction of wood species and driving method). According to the theory of orthogonal array, the withdrawal resistance for a given set of driving and extracting conditions can be approximated by the following formula :

$$P = M_i A_j + B_k + C_p + D_q + K_r - 4\mu \quad [\pm 18 : 95\% \text{ Confidence Limit}] \quad \cdots\cdots\cdots\cdots(7)$$

in which μ represents the general mean ; the capital letters, factors and the small letters, arbitrarily chosen levels. Think a set of levels $M_2A_2B_2C_2D_3K_3$ (most common case), and M_2A_2, B_2, C_2, D_3, K_3 and μ are found to be 158, 169, 180, 217, 174 and 171 from the corresponding figures. These values are substituted in formula (7), and the withdrawal resistance for the given condition can be assumed, i.e. $P=209$, while 219 is the experimental value corresponding to the same condition.

Now, M_iA_j, B_k, C_p, D_q and K_r are not continuous variables. In order to know the withdrawal resistance for arbitrarily chosen points (for example, $1<i<2$, $3<j$ and so on) of these factors, P must be expressed by a continuous function of these factors. As previously stated, the regression equations of some factors have been obtained. It is the purpose of the present section to show that all of these relations can be combined into a single formula (with good accuracy). For the surface coating and the driving direction, the regression equations have never been obtained in this report. Therefore, formulae (2), (4) and (6) are substituted in formula (7), and the withdrawal resistance for arbitrarily chosen wood species, diameters of nails and time after driving can be assumed by the following formula :

$$P = 1125G^{2.5} + 408D - 12.6 \log T - 151 \quad \text{for static driving}$$
$$P = 937G^{2.3} + 408D - 12.6 \log T - 151 \quad \text{for impact driving}$$
$$[\pm 15 : 95\% \text{ Confidence Limit}] \quad \cdots\cdots\cdots(8)$$

in which P represents the withdrawal resistance in kg for 5 cm penetration; D, the diameter of nails in cm and T, time after driving in hr.

5 Conclusions

From the experimental evidence the following conclusions can be drawn within the range tested:

1. The withdrawal resistance of the nail driven by the static load is, in general, higher than that by the impact load (Fig. 5).

2. The withdrawal resistance of nails decreases with the lapse of time after driving (Fig. 6).

3. The withdrawal resistance of nails varies remarkably with the density of the wood (Fig. 3).

4. The withdrawal resistance of nails is accurately proportional to the diameter of nails (Fig. 7).

5. The nail driven in the tangential direction generally have the largest withdrawal resistance (Fig. 8).

6. The withdrawal resistance of nails is under the control of the material coating surfaces of nails (Fig. 10).

7. The withdrawal resistance of nails for a given set of driving and extracting conditions can be approximated by the following formula:

$$P = 1125G^{2.5} + 408D - 12.6 \log T - 151 \quad \text{for static driving}$$
$$P = 937G^{2.3} + 408D - 12.6 \log T - 151 \quad \text{for impact driving}$$

in which P represents the withdrawal resistance in kg for 5 cm penetration; G, the density of the wood in g/cm^3; D, the diameter of the nail in cm and T, time after driving in hr.

Acknowledgement

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Literature Cited

1) G. Taguchi : The Design of Experiments, Vol. 1, p. 56 (Maruzen, 1958).
2) H. Sugihara : Mokuzai Kogyo (Wood Industry), 6, 351 (1951).
3) E. Gaber : Holz als Roh- und Werkstoff, 3, 224 (1940).