ラジアタマツ合板の曲げ強度と節径比の関係

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Relationship between Bending Strength and Knot Ratio of Radiata Pine Plywood

(Research note)

By

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Summary : The collation of available bending test data on radiata pine plywood is done using statistical handling for these data.

The information obtained is as follows :

The $\mathrm{MOR}_{//}$ of clear plywood is about 30% less than that of solid wood when compared at the same density. However, density is not a good indicator of the strength of even clear plywood, one reason being the varying earlywood content of the face veneer.

Knots affect strength adversely, for instance, the residual strength is estimated at only 38% at knot ratio 0.5.

The correlation between flexural rigidity and knot ratio is poor showing that knot ratio does not have a great effect on stiffness.

The regression line of strength ratio vs. stiffness ratio has a slope of less than 1, and this indicates that strength is more sensitive to the presence of knots than stiffness.

Introduction

Plywood has a long history of successful use in structures including highly stressed aircraft, concrete formwork and house sheathing.

Plywood is still considered as one of the best structural materials in wood-based materials in terms of the structural performance though some new materials such as oriented strandboard or waferboard (so called reconstituted wood products) have been developed in recent years.

Almost all plywood panels which are produced and used in Japan are made of tropical hardwood. However, considering the future situation of wood resources for manufacturing plywood, Japan should produce and import softwood plywood.

Radiata pine (*Pinus radiata* D. DON) is an acceptable and reliable species concerning its supply.

It is being planted widely in some countries in the southern hemisphere such as New Zealand, Australia and Chile, and has now been used as a peeler bolt of veneer as well as sawn structural lumber.

Most structural softwood plywood contains defects and its strength is predicted by a theory that is largely empirical, i.e. the measured strength of clear plywood is adjusted by grade factors to account for the presence of defects.

Early research work on plywood as a construction material began early in the twentieth century, and for the most part was done on clear plywood.

Recently a testing machine to bend full size panels has been developed and many in-grade tests have been conducted in the USA, Canada and Japan1).

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Using the in-grade test data, the strength and allowable stresses of plywood have been derived statistically[2] for plywood conforming to the relevant products standards.

In this paper the collation of available in-grade test data on radiata pine plywood is done using some statistical handling for these data.

Source of data, materials tested and testing methods

Though many in-grade tests have been conducted as mentioned before, very limited data are available for radiata pine plywood. Little has been published in this field.

Ten data sets have been collected including unpublished data such as limited circulations within the research institute.

These data sets are described in six research papers[3]~[8] and shown in Tables 1, 2 and 3. The peeler bolts for the plywood tested were grown in New Zealand, Australia and Chile.

The test methods employed in these studies were very different. The smallest test panel is 330 mm × 686 mm and the largest 1200 mm × 2400 mm, (i.e. full size) as shown in Table 2.

Clear properties (MOR, MOE, density, etc.) obtained from the defect-free panels vary among data sets. Density, weight of specimen air dry/volume air dry gm/cm^3, ranges from 0.501 to 0.563, $MOR_{//}$ from 52.3 to 93.1 MPa, $MOE_{//}$ from 10.6 to 13.4 GPa as shown in Table 3. $MOR_{//}$ and $MOE_{//}$ are the values for veneer within the plywood determined (by this author) using the North American parallel plies only approach, that is :

$$MOR_{//} = MOR_{APPARENT}/(I_{//}/Ip)/0.85$$

$$MOE_{//} = MOE_{APPARENT}/(I_{//}/Ip)$$

where suffix 'APPARENT' means apparent property calculated with full cross section dimensions, $I_{//}$ is the moment of inertia of parallel plies only, Ip is the gross amount of inertia and 0.85 is an empirical factor proposed by Freas[9], (the so-called K-factor).

According to the regression analysis (Fig. 1), the $MOR_{//}$ of clear plywood is about 30 percent less than that of solid wood.

This figure also shows that density is not a good indicator of the strength of even clear plywood because of the low value of coefficient of determination ($r^2 = 0.31$).

One reason for this may be the varying earlywood content of the face veneer. It may be necessary to consider the probability of occurrence of earlywood in veneer to predict the strength of plywood. However, Bier has shown in the discussion about width effect of

Table 1. List of data sets and veneer construction of plywood tested.

Data	Source	Thickness	No. of plies	Veneer construction (mm)	No. of data
A	Hirashima	7.5 mm	3	2+3.5+2	108
B	Okuma	7.5 mm	3	2.17+3.37+2.17	86
C	Leonard[1]	9.5 mm (3/8")	3	3.18+3.18+3.18	58
D	Hirashima	12.0 mm	3	4+4+4	93
E	Okuma	12.0 mm	3	4.05+4.05+4.05	106
			5	1.93+3.37+1.93+3.37+1.93	
F	Ryan	12.7 mm (1/2")	3	4.2+4.2+4.2	112
G	Bier	15.0 mm	5	3+3+3+3+3	95
H	Post	15.9 mm (5/8")	5	3.18+3.18+3.18+3.18+3.18	20
I	Leonard[1]	15.9 mm (5/8")	5	3.18+3.18+3.18+3.18+3.18	82
J	Leonard[1]	19.1 mm (3/4")	5	3.18+4.76+3.18+4.76+3.18	40

Note) 1) Only the mean value and coefficients of variation are available for particular grades of plywood.

Table 2. Summary of testing methods.

Data	Dimension of test panel (mm) (width × length)	Loading Condition	Span (mm)
A&D	854×1,820	Pure bending conforming to ASTM[1]	920 (Pure bending span)
B&E	910×1,820	Concentrated line loading by means of weights at midspan conforming to JAS[2]	900
C, I&J	914×914 in stiffness test 914×444 in rupture test	Four points loading at outer fifth points using a material testing machine	762 for 9.5 mm thick plywood, 864 for 15.9 mm thick plywood
F	330×686	Undescribed in the paper	
G	600×1,200	Four points loading at third points using a material testing machine	1,050
H	1,220×2,440	Pure bending conforming to ASTM[1]	1,676 (Pure bending span)

Note) 1) ASTM D 3043-72 Standard Methods of Testing Plywood in Flexure, Method C Pure Moment Test for Large Panels.

2) Japanese Agricultural Standard for Structural Plywood. Testing Method for Second Class Structural Plywood in Bending.

Table 3. Clear properties of veneer converted from defect-free plywood.

Data	Source	Thickness (㎜)	$\mathrm{MOE}_{//}$ (GPa)	$\mathrm{MOR}_{//}$ (MPa)	Density[1] (gm /cm^3)	No. of Sample
A	Hirashima	7.5	12.9(20.2)[2]	60.7(26.2)	0.546 (5.3)	215
B	Okuma	7.5	11.0(9.9)	—	—	13
C	Leonard	9.5	—	—	0.552[3]	58
D	Hirashima	12.0	11.3(19.0)	54.4(27.5)	0.501 (5.0)	186
F	Ryan	12.7	12.4(11.1)	85.1(15.4)	—	29
G	Bier	15.0	10.6(19.5)	68.4(20.5)	0.555 (8.5)	16
H	Post	15.9	13.4(2.1)	52.3(16.9)	—	3
I	Lenoard	15.9	13.8(11.0)	94.6(5.4)	0.563	20[4]
J	Leonard	19.1	13.2(13.1)	93.1(14.5)	0.562	40[5]

Note) 1) Density = Weight of specimen air dry/volume air dry.

2) Figures in parenthesis mean coefficients of variation (%).

3) Mean value of all panels having knots.

4) Number of samples for $\mathrm{MOR}_{//}$ is 10.

5) Number of samples for $\mathrm{MOR}_{//}$ is 20.

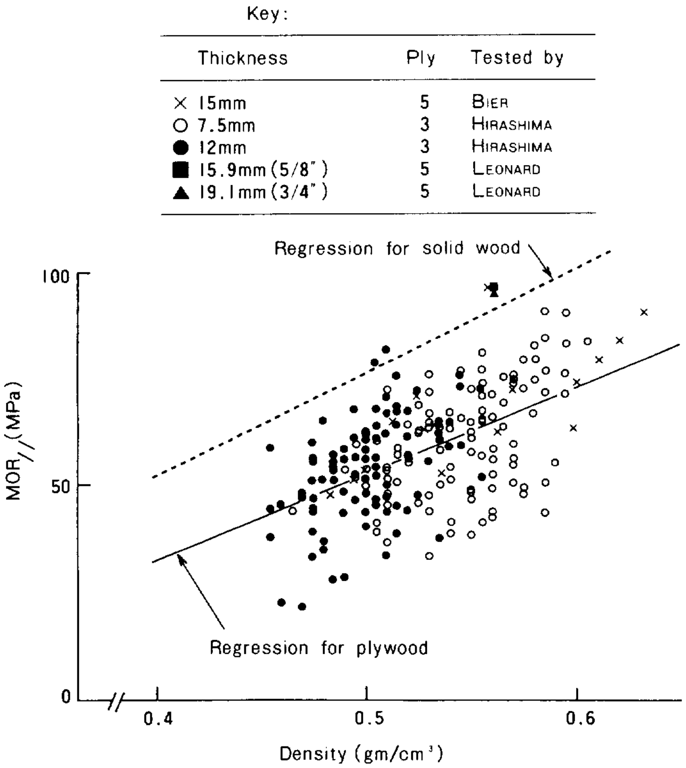

Fig. 1. Relationship between $MOR_{//}$ of knot-free plywood or solid wood[11] and density.

plywood panels that the inclusion of an earlywood content measurement did not significantly improve correlation with density (unpublished data).

The regression line obtained from the relationship between $MOE_{//}$ of plywood and density is very close to that of solid wood, as shown in Fig. 2.

Strength versus knot ratio

Results of regression analysis for some strength properties are shown in Table 4. There are some coefficients of regression which show significant difference . Some of this variation may be caused by the differences between testing methods.

Fig. 3 shows the relationship between maximum bending moment and knot ratio, the ratio of aggregate width of the knots in a panel to its width. It shows the relationship between the practical plywood performance of bending and the knot ratio. Eliminating the effect of thickness and veneer construction of the plywood, Fig. 4 shows the relationship between the strength of veneer in plywood and the knot ratio.

As shown in this figure and Table 4, the regression line for 15.9 mm thick, 5 ply plywood tested by Post has a lesser slope and is significantly different from the others. However, there is not sufficient information to determine whether the difference is caused by the difference in source (Chile), or testing method (full-size pure bending test).

The relationship between strength ratio and knot ratio is shown in Fig. 5. This strength ratio is a normalised value obtained by dividing individual values of MOR in each

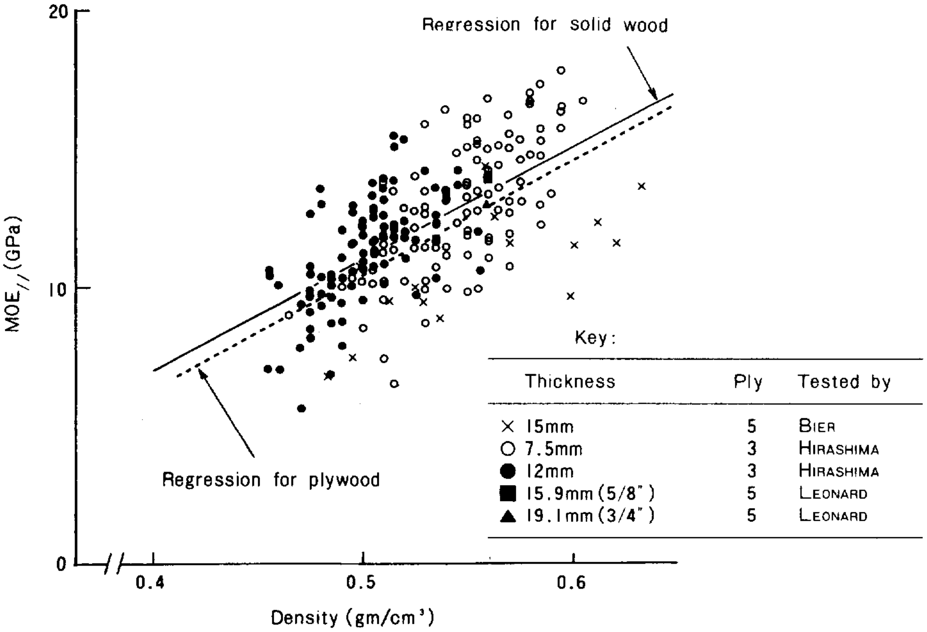

Fig. 2. Relationship between $\mathrm{MOE}_{//}$ of knot-free plywood or solid wood[10] and density.

data set by the value of the regression in Fig. 4 at a knot ratio of zero. The resulting regression lines for individual data sets are similar since there is only one combination of samples with a significant difference (Table 4). Data are scattered widely because of the diversity in strength of veneer as partially described before.

It is evident that knots affect strength adversely, for instance, the residual strength is estimated at only 38 percent at knot ratio 0.5, according to the regression line of overall data.

Stiffness versus knot ratio

Fig. 6 shows flexural rigidity plotted against knot ratio.

The correlation is poor showing that knot ratio does not have a great effect on stiffness. This is evident in Table 4 and also, when the effects of thickness and construction are eliminated (Fig. 7). For the relationship between knot ratio and stiffness ratio, poor correlations are obtained from some data sets, but slightly better correlations are also obtained from others (Fig. 8). However, when all the data are combined the stiffness of plywood decreases as the knot ratio increases (22 percent decrease at knot ratio 0.5), giving a smaller decrease than that in strength.

Strength versus stiffness

For the relationship between $\mathrm{MOE}_{//}$ and $\mathrm{MOR}_{//}$, regressions in the data obtained from full-size pure bending tests have very similar coefficients, each having gentler slope than the other testing methods (Fig. 9). Good correlation, therefore, cannot be expected in the overall data because of the differences between testing methods.

Fig. 10 shows the relationship between strength ratio and stiffness ratio, indicating the variable effects of knot on strength or stiffness.

Table 4. Results of regression analysis.

Variable		No.	Regression coefficient Y＝a＋bx		Coefficient of Determination r^2	Plywood (Data)	Test on b$^{1)}$	Combination of samples$^{2)}$
Independent X	Dependent Y		a	b				
Knot ratio	Strength ratio	1	0.765	−1.163	0.253	7.5mm, 3ply (A)		All the combi. except 4, 5
		2	0.823	−1.344	0.201	12.0mm, 3ply (D)		
		3	0.938	−0.962	0.286	12.7mm, 3ply (F)		
		4	0.947	−1.251	0.556	15.0mm, 5ply (G)		
		5	0.901	−0.652	0.353	15.9mm, 5ply (H)		
		6	0.863	−1.087	0.298	№1—№5		
Knot ratio	MOR$_{//}$	1	43.6	− 62.0	0.333	7.5mm, 3ply (A)		1, 3
		2	48.3	−117.6	0.489	12.0mm, 3ply (D)		1, 4
		3	81.9	− 83.9	0.285	12.7mm, 3ply (F)		2, 3
		4	64.7	−85.5	0.556	15.0mm, 5ply (G)		2, 4
		5	47.2	− 34.1	0.353	15.9mm, 5ply (H)		3, 4
		6	59.6	− 80.2	0.190	№1—№5		
Knot ratio	Maximum moment	1	281	− 384	0.296	7.5mm, 3ply (A)		2, 3
		2	898	−2,298	0.515	12.0mm, 3ply (D)		2, 4
		3	1,804	−1,844	0.285	12.7mm, 3ply (F)		2, 6
		4	1,657	−2,187	0.556	15.0mm, 5ply (G)		3, 4
		5	1,196	− 855	0.384	15.9mm, 5ply (H)		3, 5
		6	1,589	−1,981	0.424	15 & 15.9mm, 5ply (G,H)		3, 6
Knot ratio	MOE$_{//}$	1	9.58	1.48	0.005	7.5mm, 3ply (A)		1, 2
		2	10.4	−2.61	0.047	7.5mm, 3ply$^{3)}$(B)		1, 6
		3	12.1	−8.21	0.055	12.0mm, 3ply (D)		2, 6
		4	11.9	−8.92	0.308	12.7mm, 3ply (F)		2, 3
		5	11.1	−8.38	0.278	15.0mm, 5ply (G)		3, 4
		6	12.7	−2.79	0.085	15.9mm, 5ply (H)		3, 5
		7	11.4	−6.54	0.134	№1—№6		3, 6
								4, 5
								5, 6
Knot ratio	EI	1	30.2	4.7	0.005	7.5mm, 3ply (A)		1, 2
		2	32.9	− 8.2	0.047	7.5mm, 3ply$^{3)}$(B)		1, 7
		3	167.7	−113.8	0.055	12.0mm, 3ply (D)		2, 7
		4	96.1	− 76.5	0.355	12.0mm, 3ply or		3, 4
						5ply$^{3)}$ (E)		3, 5
		5	196.1	−147.1	0.308	12.7mm, 3ply (F)		3, 6
		6	251.1	−189.2	0.278	15.0mm, 5ply (G)		3, 7
		7	283.4	− 39.2	0.039	15.9mm, 5ply (H)		3, 10
		8	31.9	− 3.6	0.005	№1 & №2 (A,B)		4, 7
		9	181.4	−118.7	0.130	№3 & №5 (D,F)		4, 9
		10	255.0	−145.1	0.159	№6 & №7 (G,H)		5, 6
								5, 10
								7, 9
								9, 10

Table 4. (Continued)

Variable		No.	Regression coefficient Y=a+bx		Coefficient of Determination r^2	Plywood (Data)	Test on b[1]	Combination of samples[2]
Independent X	Dependent Y		a	b				
Knot ratio	Stiffness ratio	1	0.797	−0.092	0.002	7.5mm, 3ply (A)	*	1, 2
		2	0.949	−0.238	0.047	7.5mm, 3ply[3](B)	*	3, 4
		3	1.030	−0.217	0.009	12.0mm, 3ply (D)	*	3, 5
		4	0.967	−0.723	0.308	12.7mm, 3ply (F)		3, 6
		5	1.049	−0.788	0.278	15.0mm, 3ply (G)		4, 6
		6	0.949	−0.207	0.085	15.9mm, 5ply (H)	*	5, 6
		7	0.984	−0.611	0.146	No.1—No.6		
Stiffness ratio	Strength ratio	1	0.167	0.506	0.255	7.5mm, 3ply (A)		1, 3
		2	−0.018	0.703	0.273	12.0mm, 3ply (D)		1, 5
		3	−0.119	1.067	0.646	12.7mm, 3ply (F)		2, 3
		4	−0.003	0.807	0.517	15.0mm, 5ply (G)		3, 4
		5	−0.025	0.875	0.322	15.9mm, 5ply (H)		3, 5
		6	0.059	0.725	0.372	No.1—No.5		4, 5
$\mathrm{MOE}_{//}$	$\mathrm{MOR}_{//}$	1	16.77	1.64	0.108	7.5mm, 3ply (A)		1, 2
		2	8.03	2.55	0.280	12.0mm, 3ply (D)		1, 5
		3	−11.94	7.70	0.621	12.7mm, 3ply (F)		2, 5
		4	−0.226	5.19	0.517	15.0mm, 5ply (G)		4, 5
		5	−1.37	3.41	0.322	15.9mm, 5ply (H)		
		6	4.29	4.16	0.179	No.1—No.6		

Note) 1) It cannot be said within the sample attached * that Y increases (or decreases) as X increases.
2) Combination of samples in which significant difference does not exist.
3) Tested by OKUMA.

The overall regression line has a slope of less than 1. This indicates that strength is more sensitive to the presence of knot than stiffness.

Standard for plywood

Fig. 5 shows the varying limits of knot ratio specified in various standards, Japanese Agricultural Standard for Structural Plywood (JAS), U.S. Product Standard for Construction and Industrial Plywood (PS 1-74) and New Zealand Standard 3614 for Construction Plywood (NZS).

C or D grade veneer in JAS has two different knot ratios depending on the thickness of the face veneer. If the use of relevant plywood is forecasted, the limit of knot ratio should be specified to meet the performance required for the plywood, for instance in the case of sheathing, mainly flexural stiffness and allowable load.

According to the U.S. Product Standard PS 1, the limit of knot ratio for D-grade veneer is 21 percent. Thousands of tests on D-grade plywood have verified that the residual strength is 50 percent at 95 percent lower limit. If the limit of knot ratio 21 percent for D-grade veneer has been derived from the concept of required performance for plywood, the plywood having greater knot ratios than that and produced conforming to PS 1 could not meet the required performance.

However, the flexural stiffness or the strength of plywood highly depends on its

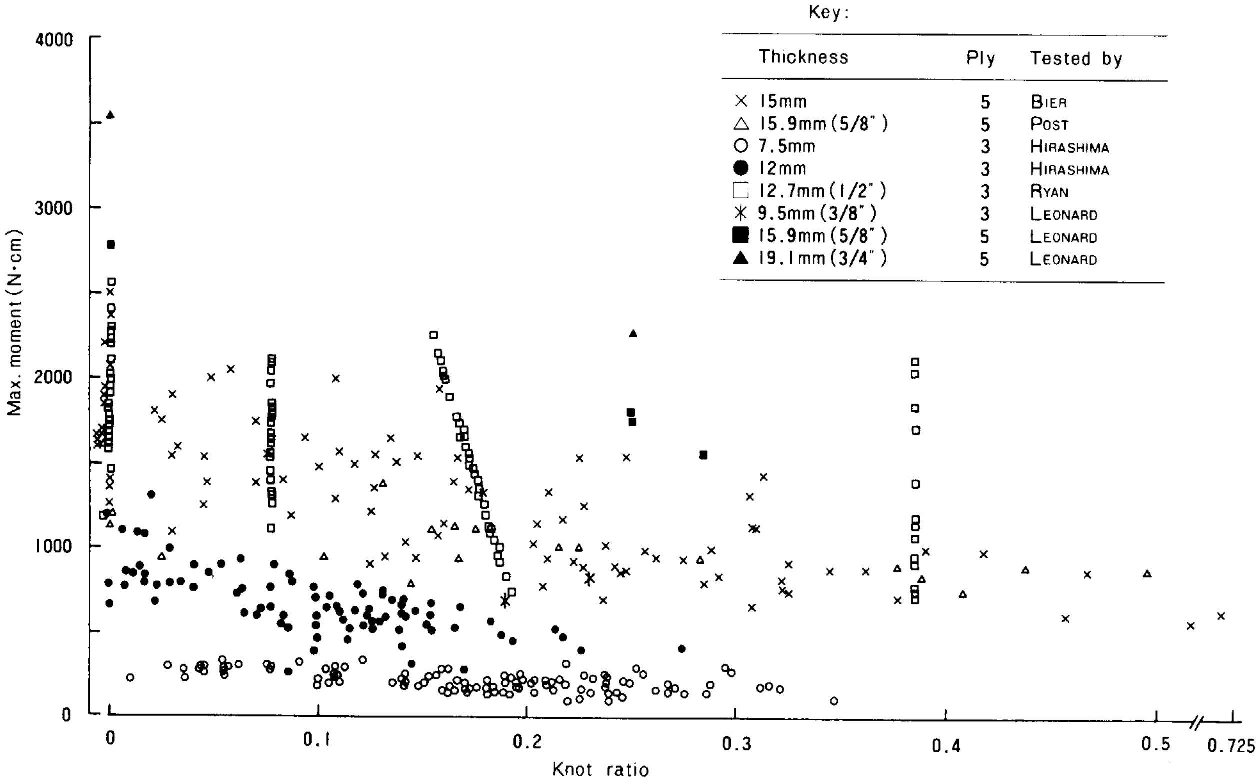

Fig. 3. Relationship between maximum moment and knot ratio.

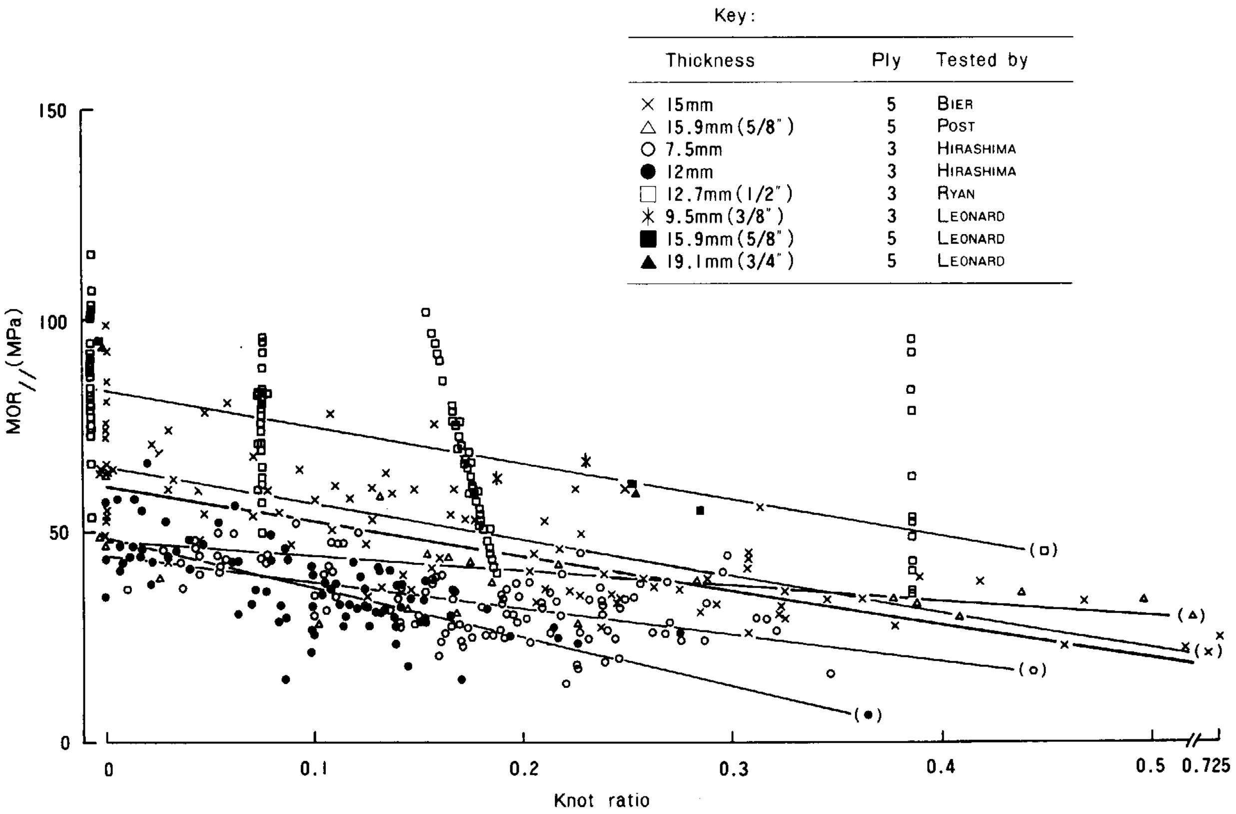

Fig. 4. Relationship between $\mathrm{MOR}_{//}$ and knot ratio

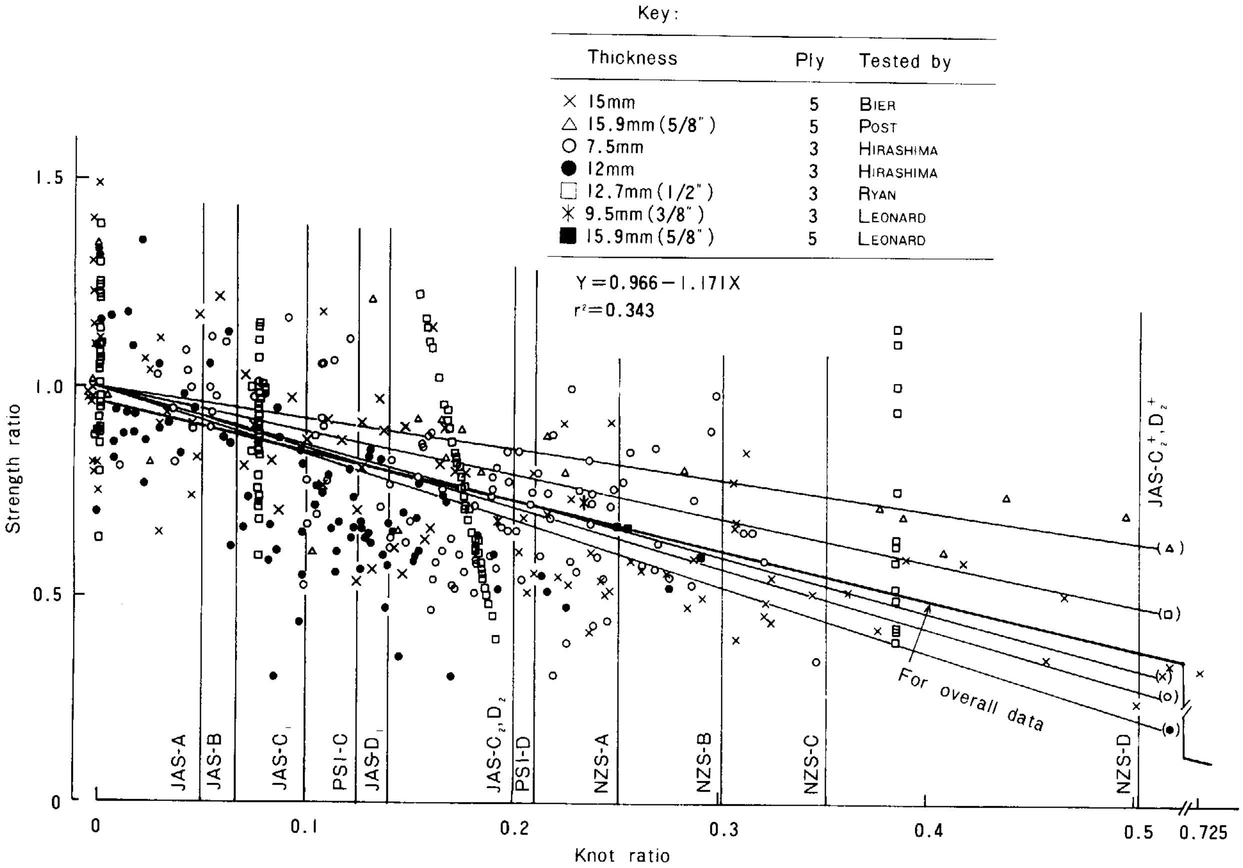

Fig. 5. Relationship between bending strength ratio and knot ratio (A, B, C, D : Veneer grade specified in standards, 1, 2 : 1st or 2nd class, + : In the case of thicker face veneer)

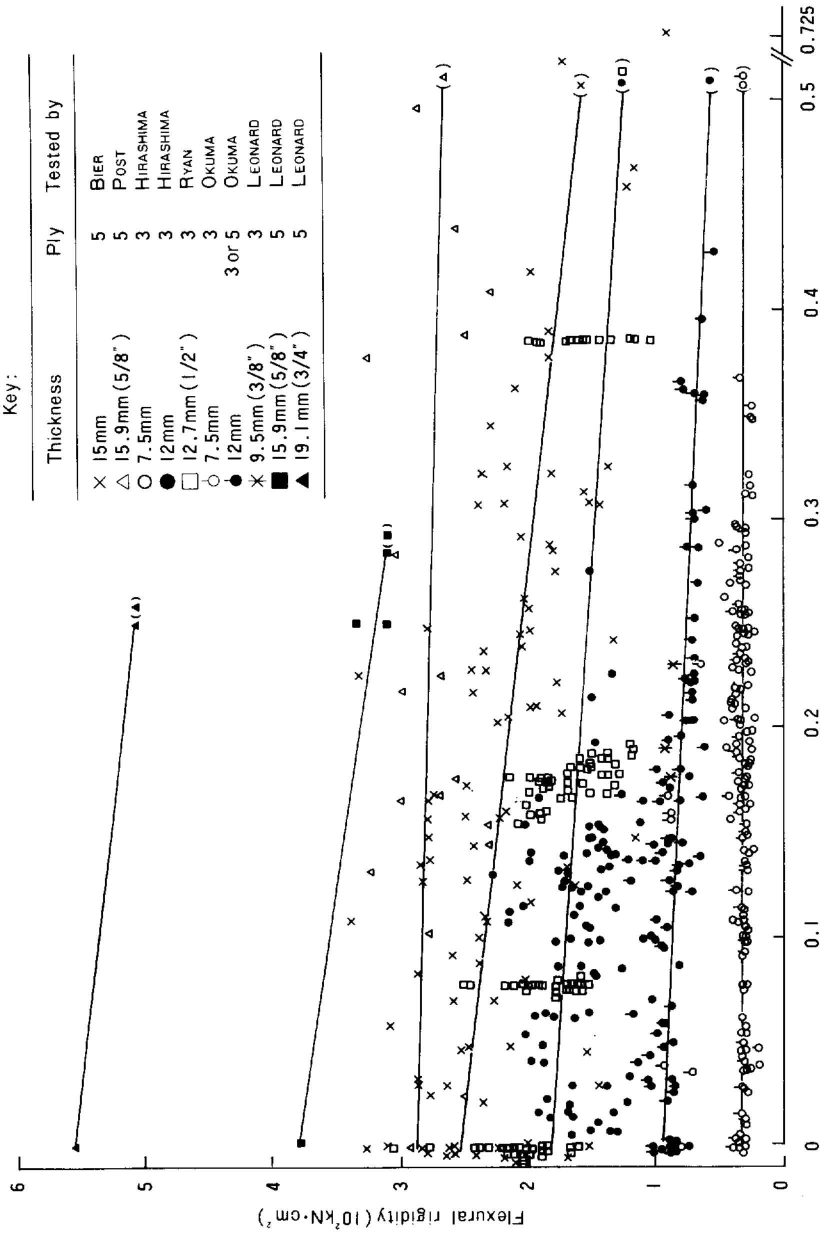

Fig. 6. Flexural rigidity (EI) vs. knot ratio.

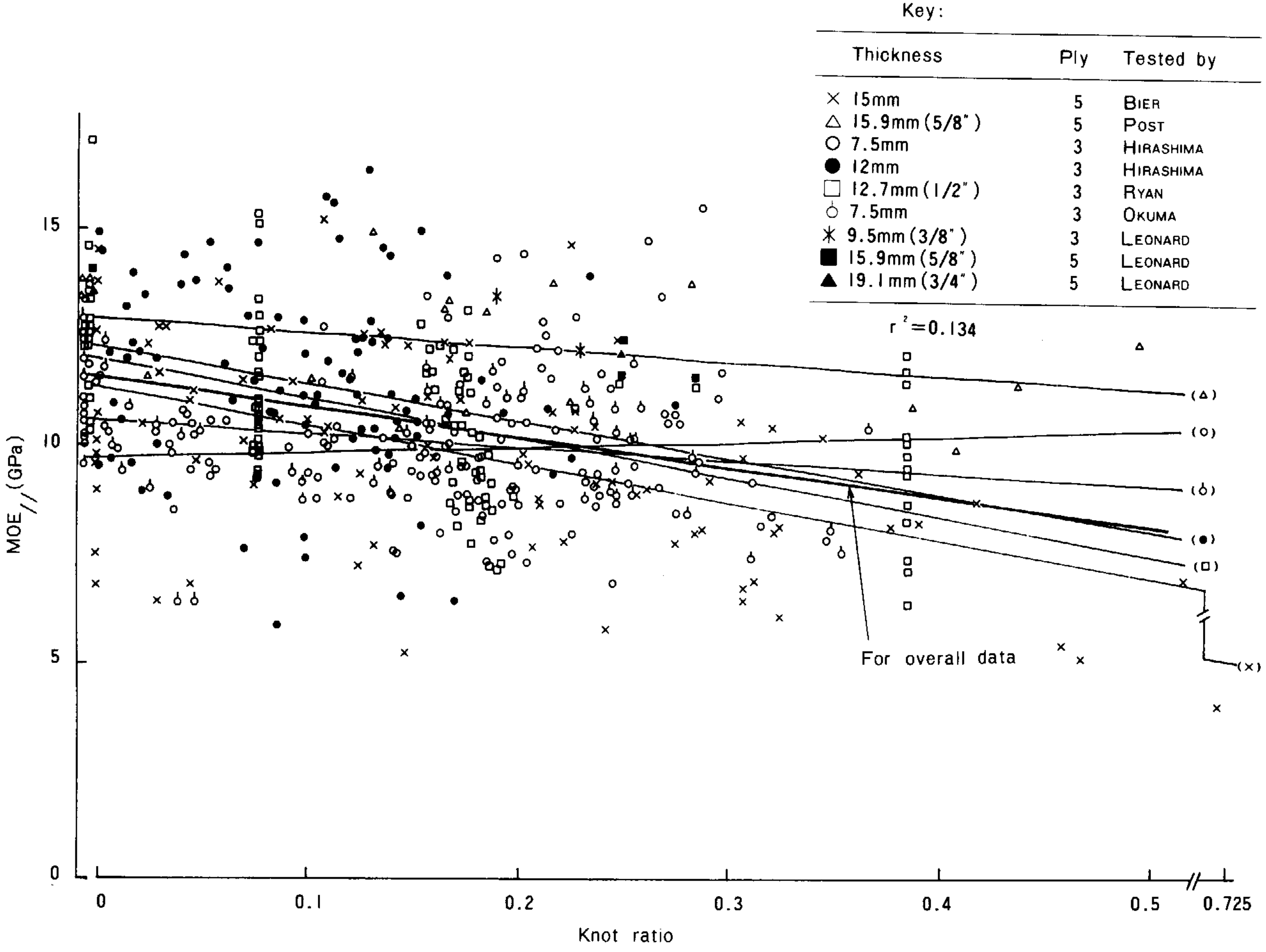

Fig. 7. $MOE_{//}$ vs. knot ratio.

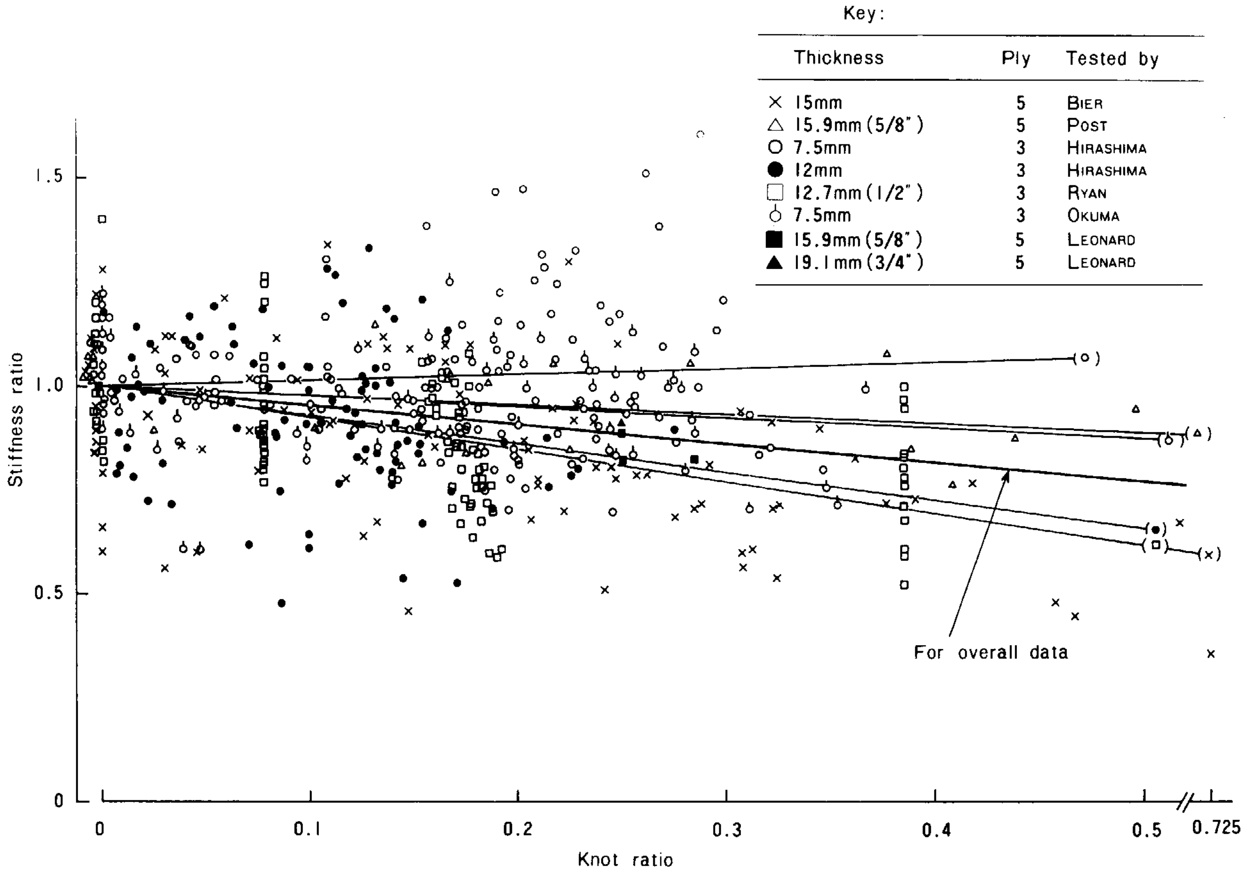

Fig. 8. Stiffness ratio vs. knot ratio.

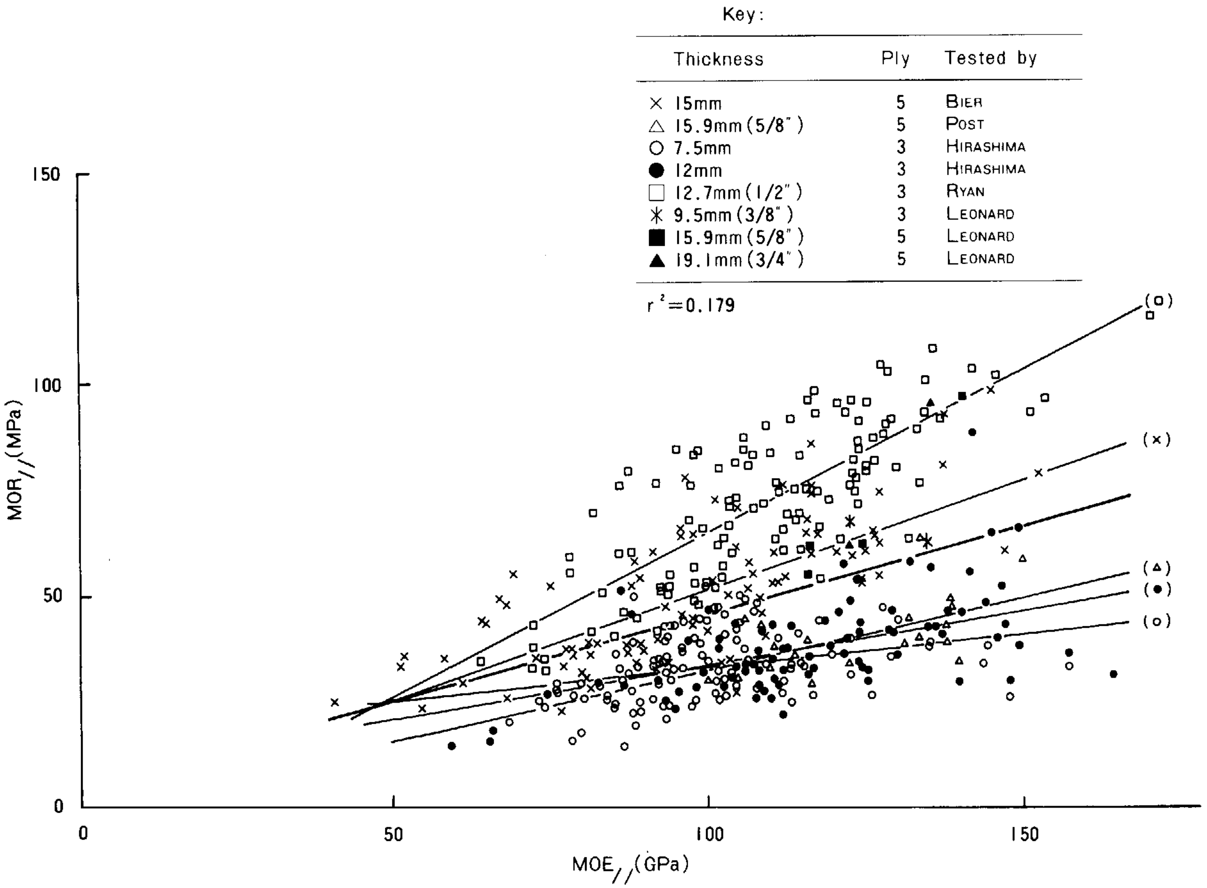

Fig. 9. $\mathrm{MOR}_{//}$ vs. $\mathrm{MOE}_{//}$

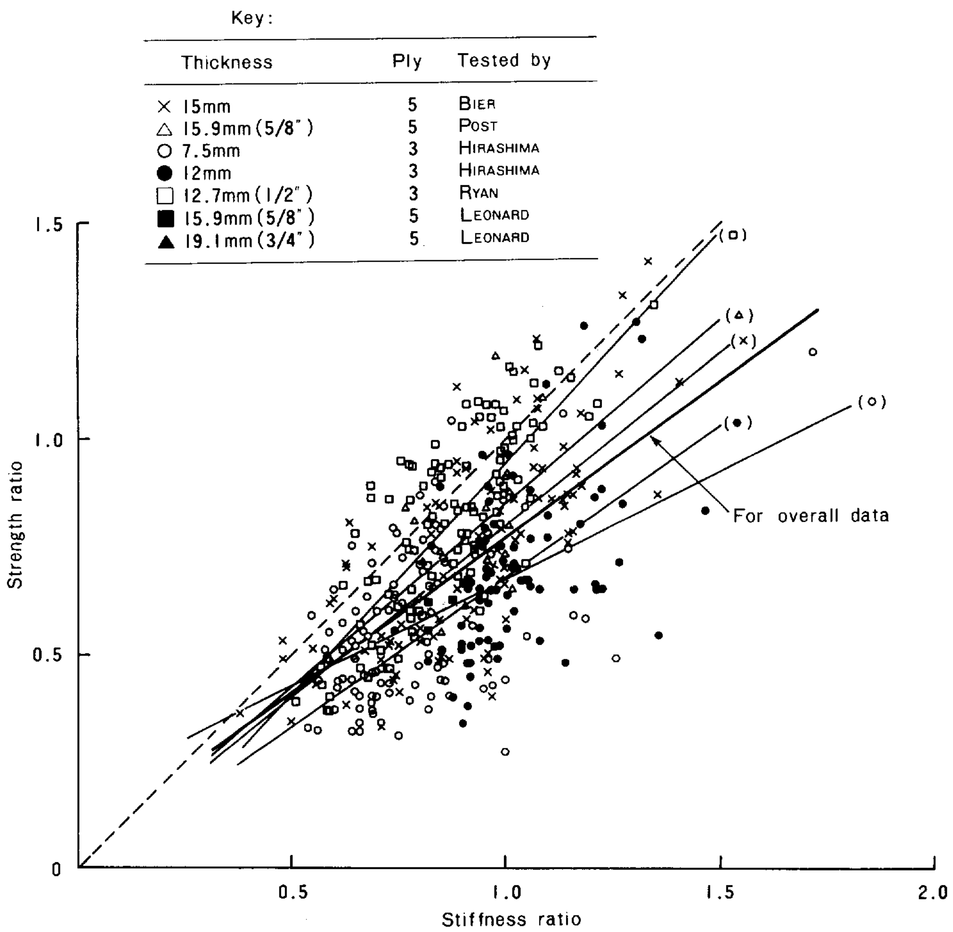

Fig. 10. Strength ratio vs. stiffness ratio.

mechanical properties varying in species used and construction of veneer.

Therefore, knot ratio should be specified for a particular construction of veneer and for a particular species with the required performance in mind.

Conclusion

Relationships between strength properties and knot size have been obtained for radiata pine plywood.

Generally, correlations are poor between them because of the variation of clear strength properties, and differences in testing methods.

For further discussions it is necessary to :

i) decide the standard testing method which can give actual strength properties of materials,

ii) analyse the variation caused by the probability of the existence of earlywood and deviation of fibres around knots,

iii) determine the variation of knot diameters and ratios within specified grade limits.

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（研究資料）

ラジアタマツ合板の曲げ強度と節径比の関係

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摘要

合板は構造的利用の分野においても，古くから幅広く用いられてきた。最近は，合板用原木の供給の逼迫化に伴い，北米等においてウエハーボードや配向性ボードといった新しい構造用パネルが開発されつつあるが，性能等の面で合板を超えるものはなく，わが国においては，やはり合板がパネル材料としての主流を占めている。

現在，わが国で生産される合板およびわが国で利用される合板の大多数は東南アジア諸国産の広葉樹材を原木としたいわゆるラワン合板である。しかし，将来の原木事情等を考えるとき，ラワン類以外の木材も検討する必要があるであろう。

特に，針葉樹合板については，わが国では，あまり製造実績や使用実績はないが，他の国においては盛んに使われているものであり，また将来，原木を造林木に頼るとするとそれは針葉樹であると考えられるので，わが国においても今のうちから検討しておく必要があると思われる。

針葉樹合板は，わが国で現在広く使われているラワン合板とは異なり，一般に表面に節が多く存在する。したがって，合板，特に針葉樹合板の強度性能を考える際には，この節の影響を考慮しなければならない。

従来の合板強度に関する研究は，節のない小試片の合板強度を基にして，節の大きさ等で強度逓減率を推定する方法が多かった。しかし，この方法では，節以外の因子による影響が捉えられず，実大の合板の強度データのばらつきには対処できなかった。

そこで，最近では，実際に節を持った大型の，時には実大の曲げ試験を行い，そのデータを統計的に処理して合板の許容応力度等を誘導することが行われるようになってきた。

本研究は，将来のわが国の合板原木として期待されるラジアタマツを使った合板について，実大またはそれに近い寸法で行われた曲げ試験データを収集し，それを統計的に解析したもので，合板の強度または剛性と，密度，節径比等との関係について論じている。

試験データ，試験方法

収集したデータは六つの報告3)~8)に含まれる10種類（Table 1，2，3）である。ラジアタマツ原木はニュージーランド，オーストラリアおよびチリー産である。試験されたパネルの寸法は，330 mm×686 mmから1200 mm×2400 mmに及んでいる。

無欠点材部の特性値

無欠点材部の曲げ破壊係数（$\mathrm{MOR}_{//}$），曲げヤング係数（$\mathrm{MOE}_{//}$），密度といった特性値もデータ間で大きな開きがある（Table 3）。

1988年1月5日受理

(1) 木材利用部

ここで無欠点材部の特性値は，合板の厚さおよび単板構成による影響を無くすため，次のような式から求めている。

$$MOR_{//} = MOR_{APPARENT} / (I_{//}/I_P) / 0.85$$
$$MOE_{//} = MOE_{APPARENT} / (I_{//}/I_P)$$

ここに添字 ‘APPARENT’ は，全断面を対象としたみかけの特性値，I_P は，平行層のみの断面２次モーメント，0.85 は Freas[9] の与えた実験定数（K ファクター）である。

回帰分析から，無欠点合板の $MOR_{//}$ は，無欠点木材のそれより約30% 低い結果が得られている（Fig. 1)。この図は又，密度は合板強度のあまりよい推定因子ではないことも示している（決定係数 0.31)。

これらの一つの理由としては，表面単板の早材部の影響が考えられる。早材部の出現は，確率的なものであり，これが強度の低下原因となり，又強度と密度の相関を悪くしていると考えられる。

$MOE_{//}$ と密度の関係は，木材のそれとよく似た関係にある（Fig. 2)。

強度と節径比

種々の強度特性の回帰分析結果を Table 4 に示す。回帰係数のうち，いくつかは，有意差のあるものがある。データ間の試験法の違いを，この原因の一つに数えることができると思われる。

Fig. 3 は，最大曲げモーメントと節径比の関係を示すもので，右下りの傾向をあらわしている。

Fig. 4 は，合板の厚さと単板構成の影響をなくした $MOR_{//}$ にしたものである。この図および Table 4 から，Post によって試験された 15.9 mm 厚，5 プライ合板は回帰直線の傾斜が緩く他のものと違った様相を示していることがよみとれる。これは，材料がチリー産であることに起因しているためなのか，試験方法が実大合板の曲げによるためなのか，あるいはその他の理由によるものなのか，ここではそれを判断する資料に乏しい。

Fig. 5 は，合板の強度を，無欠点材部の強度に対する比で表したもので，ここにおいて合板の厚さ，単板構成，無欠点材部強度の影響を除いたものとなっている。データは幅広く散らばっているがそれぞれの回帰直線はほぼ似たものとなり，傾きの有意差検定で差のあるものは一つだけであった。節が強度に与える影響は非常に大きいことが，この図から看取される。全データの回帰直線によれば，節径比が例えば 0.5 のときは強度比は 38% である。

剛性と節径比

Fig. 6 は，曲げ剛性と節径比の関係であるが，相関関係は低く，節径比が剛性に与える影響は少ないことを示している。

このことは合板の厚さや単板構成の影響をなくした値 $MOE_{//}$（Fig. 7）やさらに材質の影響をなくした値 Stiffness ratio（Fig. 8）においても看取されるところである。

強度と剛性

$MOR_{//}$ と $MOE_{//}$ に関しては，実大合板の純曲げ試験結果より得た回帰直線はそれぞれ非常によく似た結果となったが，他の試験方法によるものより，回帰直線の傾きは緩やかであり，試験法による差が現れているようである（Fig. 9)。

Fig. 10 は，$MOR_{//}$ と $MOE_{//}$ をそれぞれ規準化した値で示したもので，全体データに対する回帰直線の傾きは 1 より小さい。このことは，強度の方が剛性よりも節の影響を敏感に受けることを示している。

合板の規格

Fig. 5 に各国の規格に規定されている節径比の大きさを示した。各国の原木事情等を反映してかなり広い範囲にわたっていることが窺える。

節径比の制限は，合板に要求される性能に基づき，使用単板の強度および単板構成を考慮して定める必要があろう。

合板の強度的性質を解明するために，今後，標準的な試験方法，早材の出現確率，節周辺の繊維走行の乱れ等について検討していく必要があろう。