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A Regression Analysis for Estimating the Strength of Skin Timber Using the Density and Boring Diameter

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Skin timber can be defined as hollow timber that is circular or rectangular in cross section with an inner cavity whose cross–sectional area is more than 90% of the total cross section. Using small samples instead of full–scale skin timber, we examined the different failure types and the strength properties of bored and non–bored specimen. From these results, we prepared strength estimates as a function of the boring diameter. Adding wood density as a second independent variable, we were able to estimate the strength properties more accurately. We conclude that it will be important to perform similar measurements and regression analyses for full–scale skin timber is need, and development of hybrid structure using skin timber which can complements the strength loss of it due to its boring area is also required.

Keywords: Skin timber, failure type, regression analysis, hybrid structures

INTRODUCTION

There is an urgent need in Korea for large structural timbers of the sort that are popular for use in large commercial buildings and public facilities. With the demand for these timbers growing rapidly, there are many opinions about the best way to meet this demand. One potential solution is the use of skin timbers.

Skin timber has a number of advantages over regular timbers, such as faster drying, less drying defects, ease of chemical injection, and light weight. On the other hand, skin timber has much less strength than the traditional solid timber, and an important task is to develop a method for estimating the structural capacity of these bored–out timbers.

This study focused on pine and larch, these two wood species are widely used in Korea. Skin timber miniatures of five different diameters and non–bored common timber were tested with both load directions, perpendicular and parallel to the grain. We observed and analyzed the strength and failure types of the specimen as loads were applied.

In developing strength estimation, we used both boring diameter and wood density as independent parameters in order to increase the accuracy of the estimates. The purpose was to develop an understanding of the overall tendencies using small scale specimens rather than working with full–scale structural timbers, which are still under development. In the future, studies on full–scale skin timbers will allow us to provide more accurate and detailed data.

MATERIALS AND METHOD

Pine and larch, which are used widely in Korea as structural members, were selected for use in the study. The density of the samples was measured by KSF 2198, and their compressive strength was measured by KSF 2206–2004–06. The size of the samples used for the compressive strength test was 20×20×30 mm, according to KSF 2206.

Loading was applied in two directions, parallel and perpendicular to the grain. The testing machine was an R&B model Unitech S™, of which the maximum capacity is 10 ton. Five boring diameters were used; 2.5 mm, 4 mm, 6 mm, 8 mm and 10 mm. There were 5 samples in each group.

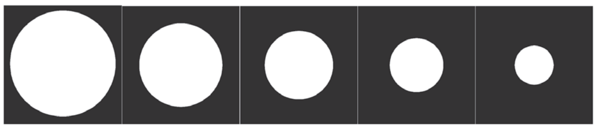

Fig. 1. An example of bored samples.

RESULTS AND DISCUSSION

Analysis of failure type for each species

Because of a lack of Korean standards, we instead used ASTM standards (ASTM 143) for our failure type analysis following a compressive test with load applied parallel to the grain.

Failure type for the compression parallel to grain

Failure types for compression parallel to the grain

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Table 1. Failure types for compression parallel to the grain

Failure type	Meaning
Crushing	This term shall be used when the plane of rupture is approximately horizontal.
Wedge split	The direction of the split, that is whether radial or tangential, shall be noted.
Shearing	This term shall be used when the plane of rupture makes an angle of more than 45 deg with the top of the specimen.
Splitting	This type of failure usually occurs in specimens having internal defects prior to test and shall be the basis for culling the specimen.
Compression and shearing parallel to grain	This failure usually occurs in cross–grained pieces and shall be the basis for culling the specimen.
Brooming or end rolling	This type of failure is usually associated with either an excess moisture content at the ends of the specimen, improper cutting of the specimen, or both.

were classified into 6 types, as shown in Table 1. This follows ASTM D 143–94 (Reapproved 2007).

–Failure types for compression parallel to the grain for pine

When failure modes were in mixture, each failure types were together represented. In the case of compression parallel to the grain of pine, as shown in Table 2, the wedge split type and the brooming type appeared most frequently, followed by crushing, shearing, and splitting, which rarely appeared. There was no compression or shearing parallel to the grain. That can possibly be explained by the absence of cross–grains in the specimen used. An example of each failure type for compression parallel to the grain of pine is shown in Table 3.

– Failure types for compression parallel to the grain for larch.

The failure types for compression were different in larch from those in pine. As shown in Table 4, for compression parallel to grain of larch, crushing appeared most frequently, followed by wedge split, brooming, splitting, and shearing type. There was no compression or shearing parallel to the grain because of the absence of cross–grains in the samples, as same as the case of pine. Examples of each failure type for compression parallel to the grain of larch are shown in Table 5.

Failure types for compression perpendicular to the grain

Compression perpendicular to the grain has less meaning than compression parallel to the grain. Construction members should not be under compression perpendicular to the grain during construction work because strength in the direction perpendicular to the grain is so low. However, in this study, the observation under compression perpendicular to the grain was done to evaluate whether they could keep their original shape (rectangular shape) or distort laterally, and whether the bored circular shape could keep their original shape or

Table 2. Failure types for compression parallel to the grain for pine

Specimen		Failure type	Specimen		Failure type
Control	1	Crushing	6 mm	1	Shearing
	2	Wedge split/Shearing		2	Wedge split
	3	Shearing		3	Crushing
	4	Brooming		4	Crushing/Brooming
	5	Wedge split		5	Crushing/Brooming
Specimen		**Failure type**	**Specimen**		**Failure type**
2.5 mm	1	Wedge split	8 mm	1	Crushing
	2	Wedge split		2	Wedge split
	3	Brooming		3	Brooming
	4	Wedge split		4	Brooming
	5	Brooming		5	Crushing
Specimen		**Failure type**	**Specimen**		**Failure type**
4 mm	1	Wedge split	10 mm	1	Splitting
	2	Wedge split		2	Brooming
	3	Shearing		3	Splitting
	4	Wedge split/Splitting		4	Brooming
	5	Brooming		5	Crushing

Table 3. Examples of each failure type for compression parallel to the grain for pine

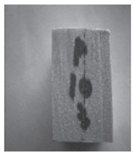
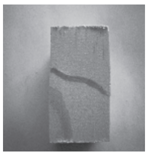
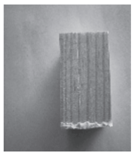
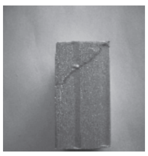
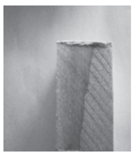
Failure type	Sample	Failure type	Sample
Crushing		Splitting	
Wedge split		Compression and shearing parallel to grain	–
Shearing		Brooming or end rolling	

Table 4. Failure type for compression parallel to the grain for larch

Specimen		Failure type	Specimen		Failure type
	1	Crushing		1	Wedge split/Splitting
	2	Crushing		2	Wedge split/Splitting
Control	3	Brooming	6 mm	3	Splitting
	4	Wedge split		4	Splitting
	5	Brooming		5	Crushing/Wedge split
Specimen		**Failure type**	**Specimen**		**Failure type**
	1	Crushing		1	Wedge split
	2	Shearing		2	Crushing
2.5 mm	3	Brooming	8 mm	3	Brooming
	4	Crushing		4	No failure
	5	Wedge split		5	Crushing
Specimen		**Failure type**	**Specimen**		**Failure type**
	1	Crushing		1	Brooming
	2	Brooming		2	Wedge split/Splitting
4 mm	3	Crushing	10 mm	3	Brooming
	4	Crushing		4	Wedge split/Crushing
	5	Shearing		5	Wedge split/Splitting

Table 5. Sample of each failure type for compression parallel to the grain for larch

Failure type	Sample	Failure type	Sample
Crushing		Splitting	
Wedge split		Compression and shearing parallel to grain	–
Shearing		Brooming or end rolling	

lose it.

– Failure types for compression perpendicular to the grain for pine and larch.

'Distortion' means deformation after loading with a loss of the original square shape; 'former state' means maintaining the original shape after loading, without internal or boring failure. If a perfect failure developed around the boring, 'crack' was added. Fig. 2 and Fig. 3 show a cracked sample as well as a non–cracked specimen. Each failure types for compression perpendicular to the grain for pine and larch were suggested in Table 6 and Table 7.

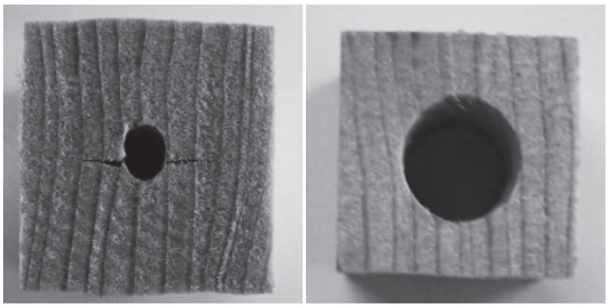


Fig. 2. Cracked specimen (left: 4 mm–No. 5) and non–cracked specimen (right: 10 mm–No. 2) for load perpendicular to grain (pine).

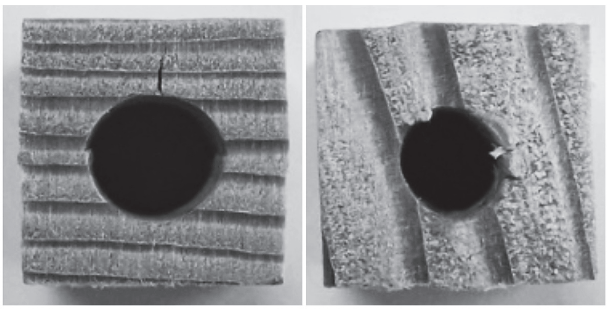


Fig. 3. Cracked specimen (left: 10 mm–No. 3) and non–cracked specimen (right: 8 mm–No. 2) for load perpendicular to the grain (larch).

Derivation of the regression equation

A regression equation in two variables, the boring diameter (independent variable) and the compressive strength (dependent variable), was derived through an analysis of variance for each species. For more accuracy, we also performed an analysis of variance for two variables simultaneously with the addition of a second independent variable representing density. The necessary data were represented in Table 8.

– Regression equations for the estimation of the compressive strength for pine

When only one independent variable, the boring diameter was considered, the coefficient of determination was 0.73, which means that it was possible to estimate the strength performance with considerable accuracy with just one variable. The coefficient of determination rose to 0.86 when density was added as a second independent variable (Appendix Pine 1). The higher the coefficient of determination, the more accurate the estimation equation is. Table 9 shows regression equations for estimating the compressive strength.

– Consideration of only bored specimens; exception of non–boring specimen

The variation of the non–bored sample was greater than that of the five bored specimens. Thus, we performed an additional regression analysis without the control group (that is, the non–bored samples), which had greater variation. The results are Appendix Pine 2.

When the regression equation was derived without the non–bored samples, there was an increase in the

Table 6. Failure types for compression perpendicular to the grain for pine

Specimen		Failure type	Specimen		Failure type
Control	1	distortion	6 mm	1	distortion
	2	distortion		2	distortion
	3	former state		3	distortion
	4	distortion		4	distortion
	5	former state		5	distortion
Specimen		**Failure type**	**Specimen**		**Failure type**
2.5 mm	1	crack/former state	8 mm	1	distortion
	2	distortion		2	distortion
	3	distortion		3	former state
	4	distortion		4	former state
	5	distortion		5	former state
Specimen		**Failure type**	**Specimen**		**Failure type**
4 mm	1	crack/former state	10 mm	1	former state
	2	crack/distortion		2	former state
	3	crack/former state		3	distortion
	4	distortion		4	former state
	5	crack/former state		5	distortion

Table 7. Failure types for compression perpendicular to the grain for larch

Specimen		Failure type	Specimen		Failure type
Control	1	former state	6 mm	1	distortion
	2	distortion		2	distortion
	3	distortion		3	crack/distortion
	4	distortion		4	crack/distortion
	5	former state		5	crack/distortion
Specimen		**Failure type**	**Specimen**		**Failure type**
2.5 mm	1	former state	8 mm	1	crack/distortion
	2	former state		2	former state
	3	distortion		3	former state
	4	distortion		4	distortion
	5	crack/distortion		5	distortion
Specimen		**Failure type**	**Specimen**		**Failure type**
4 mm	1	crack/distortion	10 mm	1	former state
	2	distortion		2	former state
	3	crack/distortion		3	crack/former state
	4	distortion		4	crack/distortion
	5	crack/distortion		5	distortion

Table 8. Mechanical and physical properties of samples

	O.D		Parallel to grain (MPa)				Perpendicular to grain (MPa)			
			Pine		Larch		Pine		Larch	
	Pine	Larch	Compre–ssive strength	Proportional limit strength	Compre–ssive strength	Proportional limit strength	Compre–ssive strength	Proportional limit strength	Compre–ssive strength	Proportional limit strength
Non–boring	0.5	0.53	40.97	34.53	50.19	44.5	6.91	4.3	9.09	6.53
2.5 mm	0.5	0.49	44.16	35.47	46.06	41.67	11.99	6.82	8.73	6.22
4 mm	0.5	0.52	41.56	33.72	48.42	43.11	9.26	7.53	10.62	5.93
6 mm	0.48	0.48	40.23	34.31	55.09	49.13	3.9	3.5	4.5	3.12
8 mm	0.46	0.5	34.37	27.5	47.05	42.34	6.55	5.38	5	3.58
10 mm	0.46	0.49	31.04	25.43	45.38	38.11	4.66	4.12	5.21	3.55

Table 9. Regression equations for the estimation of the compressive strength of pine

Independent variables	Equation
Only diameter	compressive strength=(–1.15562 * diameter of hollow)+44.5953
Diameter+density	compressive strength=(–0.0224 * diameter of hollow)+(229.6336 * density)–72.1548

Table 10. Advanced regression equations for the estimation of the compressive strength of pine

Independent variables	Equation
Only diameter	compressive strength=(–1.7664 * diameter of hollow)+49.04614
Diameter+density	compressive strength=(–1.76102 * diameter of hollow)+(0.850162 * density)+48.60511

coefficient of determination both loads, perpendicular and parallel to the grain. Thus, a more accurate estimate of the dependent variable was possible. The coefficient of determination increased from 0.73 to 0.97 when only one variable, the diameter of boring, was used for the regression equation, and it increased from 0.86 to 0.97 when density was added as a second independent variable. The regression equations derived for the bored samples without data from the non–bored sample are shown in Table 10.

– Regression equations for the estimation of the compressive strength of larch

The measured strength varied greatly among the groups of larch. In case of one variable consideration, boring diameter considered as an independent variable, the regression analysis resulted in a low coefficient of determination of 0.06. On the contrary, in case of two

Table 11. Regression equations for the estimation of the compressive strength of larch

Independent variables	Equation
Only diameter	compressive strength=(−0.23423 * diameter of hollow)+49.8882
Diameter+density	compressive strength=(−0.44878 * diameter of hollow)+(−66.81 * density)+84.4952

variable consideration, the density was added a independent variable, the regression analysis resulted in slightly high value of 0.14 (Appendix Larch 1). However, as the variation of the samples with a boring diameter less than 4mm was very great, we performed additional regression analysis without those samples. The results were presented in Table 11.

– Regression analysis for the data with boring diameter over than 4 mm

Just as an additional regression analysis was conducted for the pine samples with the data for the non–bored samples omitted, we performed a regression analysis for larch that omitted the data for the samples with boring diameter less than 4 mm, as the variation among those samples was quite large and had no special grouping characteristics. The results are Appendix Larch 2. The coefficient of determination was 0.06 for the analysis using diameter of boring as the only independent variable and 0.14 for the analysis with diameter of boring and density as two independent variables. On the other hand, when we removed the data for samples with a boring diameter less than 4 mm, the coefficient of determination increased to 0.87, implying that much more accurate estimation would be possible.

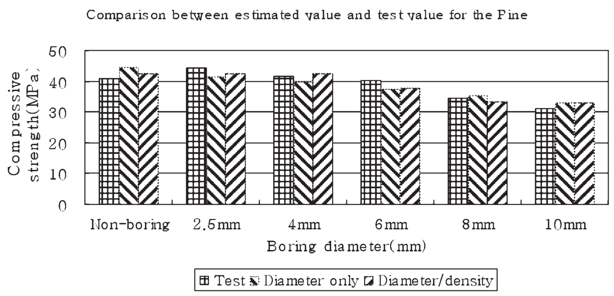


Fig. 4. Comparison between the estimated value and the tested value for pine.

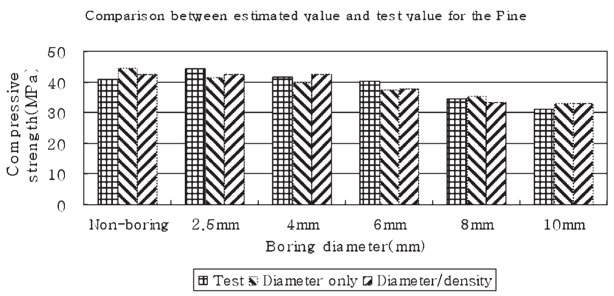


Fig. 5. Comparison between the estimated value and the tested value for larch.

Comparison between estimated values and tested values

There was a significant difference between estimated value and the test value when the regression analysis used only one variable, the boring diameter, for the pine. The error was reduced considerably, however, when we added density as a second variable to the regression analysis, as shown in Fig. 4. The difference is reduced even more, if the regression analysis is performed with the data from the non–bored specimens excluded, as described in the previous paragraph (Table 10).

For larch, when the regression took into account only the boring diameter, there was very little correlation between the estimated value and the tested value, as shown in Fig. 5. The correlation was increased somewhat with the addition of density as a second independent variable. The correlation was increased greatly by omitting data for samples with a boring diameter less than 4 mm, as shown in previous paragraph.

CONCLUSION

Using small miniature samples instead of full–scale skin timber, we examined the different failure types and the strength properties of bored and non–bored specimen. From these results, we prepared strength estimates as a function of the boring diameter. When we added density as a second independent variable, we were able to estimate the strength properties far more accuracy.

The predominant failure types for pine were brooming and wedge type when the load was applied parallel to the grain. For larch, with a load applied parallel to the grain, the predominant failure type was crushing.

The strength estimation equations for pine derived from the regression analysis were 'compressive strength = (−1.76643×diameter of boring) + 49.04614' when only diameter of boring considered, 'compressive strength = (−1.76102×diameter of boring) + (0.850162×density) + 48.60511' when additionally density considered. For larch, the equations were 'compressive strength = (−0.23423×diameter of boring) + 49.8882' and 'compressive strength = (−0.44878×diameter of boring) + (−66.81×density) + 84.4952', respectively.

We conclude that it will be important to perform similar measurements and regression analyses for full–scale skin timber is need, and development of hybrid structure using skin timber which can complements the strength loss of it due to its boring area is also required.

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APPENDIX

Pine 1–1

Summary (Diameter only)

Regression statistics	
Multiple R	0.854231
R Square	0.72971
Adjusted R square	0.662138
Standard Error	2.882953
Observations	6

Anova

	df	SS	MS	F	Significance F
Regression	1	89.75453	89.75453	10.79895	0.030324
Residual	4	33.24566	8.311416		
Total	5	123.0002			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	44.5953	2.140283	20.83617	3.14E–05	38.65292	50.53768
X 1	–1.15562	0.351662	–3.28617	0.030324	–2.132	–0.17925

Pine 1–2

Summary (Diameter+density)

Regression statistics	
Multiple R	0.925668
R Square	0.856862
Adjusted R square	0.761437
Standard Error	2.422533
Observations	6

Anova

	df	SS	MS	F	Significance F
Regression	2	105.3942	52.6971	8.979403	0.054154
Residual	3	17.60599	5.868664		
Total	5	123.0002			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	–72.1548	71.54023	–1.00859	0.387465	–299.828	155.5181
X 1	–0.0224	0.754454	–0.0297	0.978174	–2.42342	2.378606
X 2	229.6336	140.6667	1.632466	0.201085	–218.031	677.2977

Pine 1–2

Summary Diameter only

Regression statistics	
Multiple R	0.982861
R Square	0.966016
Adjusted R square	0.954688
Standard Error	1.150887
Observations	5

Anova

	df	SS	MS	F	Significance F
Regression	1	112.9534	112.9534	85.27733	0.002686
Residual	3	3.973624	1.324541		
Total	4	116.927			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	49.04614	1.275306	38.45833	3.87E–05	44.98755	53.10473
X 1	–1.76643	0.191284	–9.23457	0.002686	–2.37518	–1.15767

Pine 2–2

Summary (Diameter+density)

Regression statistics	
Multiple R	0.982862
R Square	0.966017
Adjusted R square	0.932034
Standard Error	1.409525
Observations	5

Anova

	df	SS	MS	F	Significance F
Regression	2	112.9535	56.47673	28.42652	0.033983
Residual	2	3.973524	1.986762		
Total	4	116.927			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	62.11216	0.782538	0.515841	–218.642	315.8522	
X 1	0.795758	–2.21301	0.157363	–5.18489	1.662847	
X 2	119.6948	0.007103	0.994978	–514.155	515.8554	X 2

Larch 1–1

Summary Diameter+density

Regression statistics	
Multiple R	0.240288
R Square	0.057738
Adjusted R square	–0.17783
Standard Error	3.878639
Observations	6

Anova

	df	SS	MS	F	Significance F
Regression	1	3.68732	3.68732	0.245105	0.646505
Residual	4	60.17537	15.04384		
Total	5	63.86269			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	49.8882	2.879474	17.32546	6.51E–05	41.8935	57.8829
X 1	–0.23423	0.473116	–0.49508	0.646505	–1.54781	1.07935

Larch 1–2

Summary Diameter+density

Regression statistics	
Multiple R	0.375401
R Square	0.140926
Adjusted R square	–0.43179
Standard Error	4.276401
Observations	6

Anova

	df	SS	MS	F	Significance F
Regression	2	8.999889	4.499945	0.246065	0.796244
Residual	3	54.8628	18.2876		
Total	5	63.86269			

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	84.4952	64.28657	1.314352	0.280185	–120.093	289.0838
X 1	–0.44878	0.656175	–0.68394	0.543106	–2.53703	1.639456
X 2	–66.81	123.956	–0.53898	0.627328	–461.293	327.6733

Larch 2

Summary Diameter only

Regression statistics	
Multiple R	0.935362
R Square	0.874903
Adjusted R square	0.749806
Standard Error	2.5973
Observations	3

Anova

	df	SS	MS	F	Significance F	F critical
Regression	1	47.17984	47.17984	6.993785	0.230147	2.620654
Residual	1	6.745966	6.745966			
Total	2	53.9258				

	Coefficient	Standard Error	t Stat	P–value	Lower 95%	Upper 95%
Intercept	68.59939	7.497759	9.14932	0.069306	–26.6687	163.8674
X 1	–2.42847	0.918284	–2.64458	0.230147	–14.0964	9.239434