A Study of Fracture Features and Fracture Toughness on CT Tests with Some Structural Glued-Laminated Timber

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ABSTRACT

At the connections in timber structures loaded perpendicular to grain, the wood sometimes fractures in brittle or ductile. To this problem, some researchers conducted some type tests, and analyzed. But there isn't a standard evaluation method. Additionally someone used very clear wood, so the dates for the general wood for the timber construction is lacking.

In this study, we conducted CT tests with some structural glued-laminated timber. The wood species are Scots Pine, Japanese Larch and Japanese cedar, they frequently are processed into structural glued-laminated timber (hereinafter referred to as "glulam").

We used initial crack-lengths and thickness as parameters. The ratios, a_0/W, are 0.26, 0.41, 0.50, 0.6, these values were referred to JSME. Thicknesses are 47mm, 94mm and 150mm.

As the results, in the case its thickness is under 94mm and the a_0/W is over 0.50, we can see ductile fracture of wood in stable, we can obtain stable value of J-integral for crack initiation.

1. Introduction

Splitting of wood loaded perpendicular to the grain is a critical issue in timber engineering, and the splitting and failure of wood at its connection are studied in some articles. But to research the characterization and to evaluate that fracture is very difficult. So we need a method to evaluate the fracture properly and to apply the criteria to some type connections. And many researchers used very clear wood to conduct some type tests, so we need many date of the general woods for structural constructions.

Thus we conducted CT tests with some woods for structural glued-laminated timber. Then we prepared the specimens which has different crack length and different width. In those tests, we checked the behavior of crack initiation and propagation on both side surfaces. We calculated J-integral with the experimental results.

2. SPECIMENS AND TEST PROCEDURE

2.1 MATERIALS

For the specimens, three glulam-beams were made of Scots pine, Japanese larch and Japanese cedar. The beams were made of the same grade laminae for each wood. For the beams of Scots pine or Japanese larch, L110 graded laminae were used, and for Japanese cedar, L60 graded laminae were used. The beams were 150mm width, 120mm depth and 3500mm length. They were cut into three-small-beams which were 47mm width, and named them 1), 2) and 3), as shown in Fig.1. All specimens were cut from these small beams. Specimens were selected to avoid knots or other defects. However it is not sure that the annual rings are parallel, as shown in Photo1. We measured each line's angle of gradient for annual rings indicated in the right of Fig.1. The results were followings; 1) 46.4[deg.], 2) 22.4[deg.], 3) 18.4[deg.] for Scots pine, 1) 23.7[deg.], 2) 6.0[deg.], 3) 22.6[deg.] for Japanese larch, 1) 12.5[deg.], 2) 21.3[deg.], 3) 45.9[deg.] for Japanese cedar. The average densities of each wood were 0.49 for Scots pine, 0.51 for Japanese larch, 0.33 for Japanese cedar. And we checked the moisture content on surface under 18% with a portable measure.

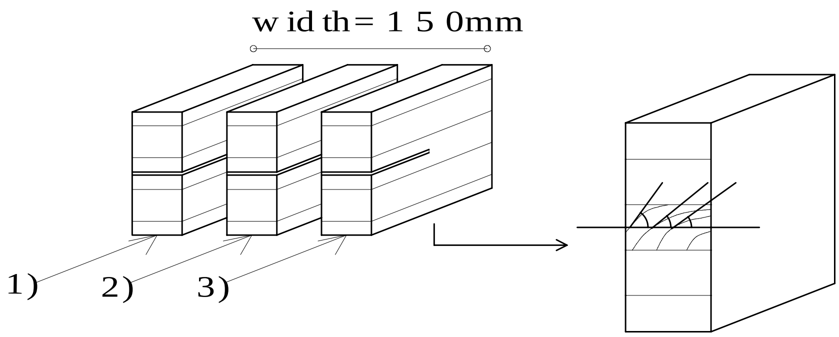

Fig.1 Glulam beams and measure method of annual rings

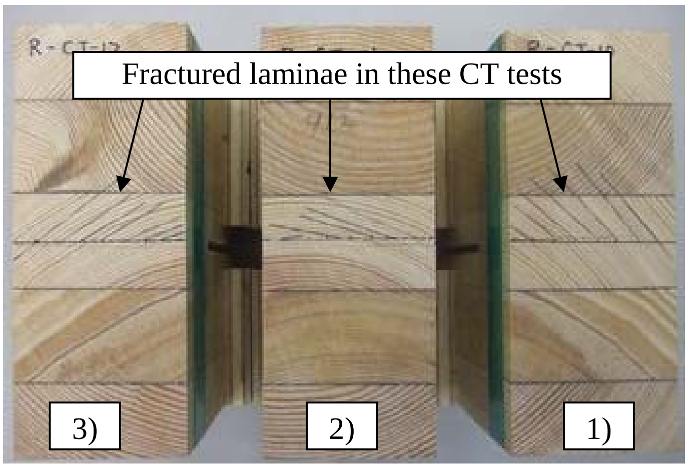

Photo 1 examples of the cross-section and annual rings (Scots Pine)

2.2 Test method

In this study we conducted CT tests. For the first step, we analyzed the affect of initial crack length with the specimens. The specimen's geometry was based on the Standard Method of Test for Elastic-Plastic Fracture Toughness J_{1C} [1]. The basic geometry was in Fig.2. Its width (B) was 47mm, its length (W) was 94mm.

These type specimens were cut from above small-beams. The initial crack length is defined from 0.5 to 0.75 with dimensionless-crack length, a_0/W in the Standard [1]. We employed 0.26, 0.4, 0.5 and 0.6 for dimensionless-length.

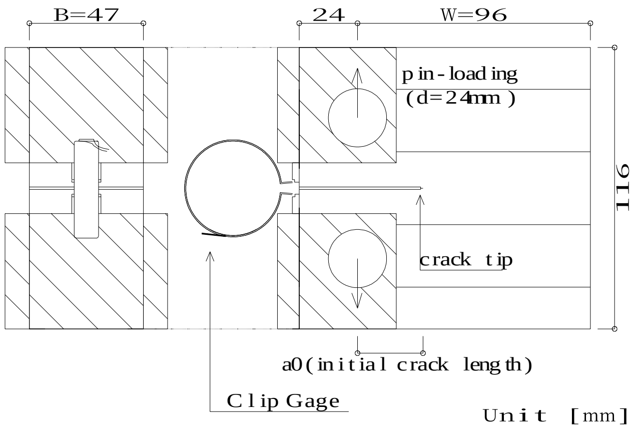

Fig.2 Specimens geometry (B=47mm)

For the second step, we analyzed the affect on the width and initial crack length. From the results of the first step tests, the fracture toughness didn't differ as the dimensionless-crack length were 0.5 and 0.6. Then we employed 0.26, 0.4 and 0.5 for dimensionless-length. And we prepared the specimens which width (B) are 94mm and 150mm. The parts of 2) and 3) in the original beams were used for the specimens which width were 94mm. And the specimens which width was 150mm were original width of the beam.

The experimental situation is in Photo 2. The loaded speed is 0.5mm/min. Load, load-point-displacement and crack opening displacement (COD) were measured. The 1mm-spacing grids were on the specimens in front of the crack tip as shown in Photo 3. We checked the behavior of crack initiation and propagation with two video cameras indicated in Photo2.

The method to procedure the initial crack is following;

1) cut the specimen with a saw which width is 3mm. 2) At that time, we cut it for the front of target crack-length. 3) For the left 1mm-part, we cut with a knife. To make a parallel crack to end, we slide the knife into the wood by putting the knife-end with loading machine.

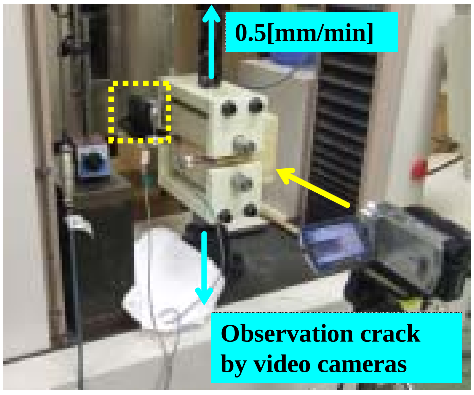

Photo 2 experimental situation

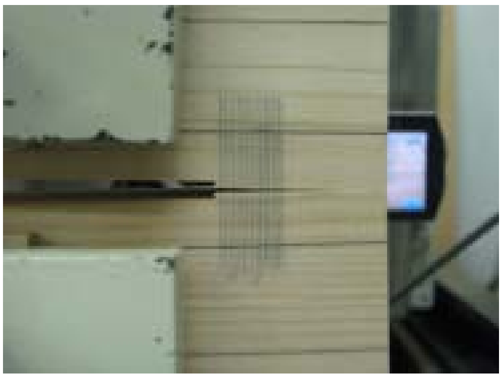

Photo 3 Grids on the specimen and crack propagation

3. Test results and discussion

3.1 Test results and fracture characteristic

In the first and second type tests, specimens were fractured from the initial crack. There was three types fracture features from macroscopic results.

The first type is brittle fracture. In this case, we can see linear behavior in load-displacement relationship. At the maximum load, the load got down to almost zero indicated in the left of Fig.3. We can hear the big sound at fractured point.

The second type is ductile fracture. In this case, we could see the crack propagation on the video and sounded a little. Its propagation speed was not stable, both side cracks didn’t start at once. The characteristic of crack propagation in ductile fracture were followings;

1) Cracks propagated about 10mm in a moment, stopped, and propagated again.

2) Cracks propagated under 10mm slowly, stopped and propagated again.

On this ductile fracture, we could get a continual load and displacement relationship as shown in the right of Fig.3.

The third one is in-between fracture type with brittle and ductile. We called this type not-Brittle fracture on trial. In this case, we heard a sound (less than that of Brittle fracture) near the maximum load, but the load didn’t got down rapidly to zero. On the relationship with load and displacement indicated in the center of Fig.3, when crack start to initiate, its load-value got down a little, however after that, load decreased slowly and crack propagated like ductile fracture.

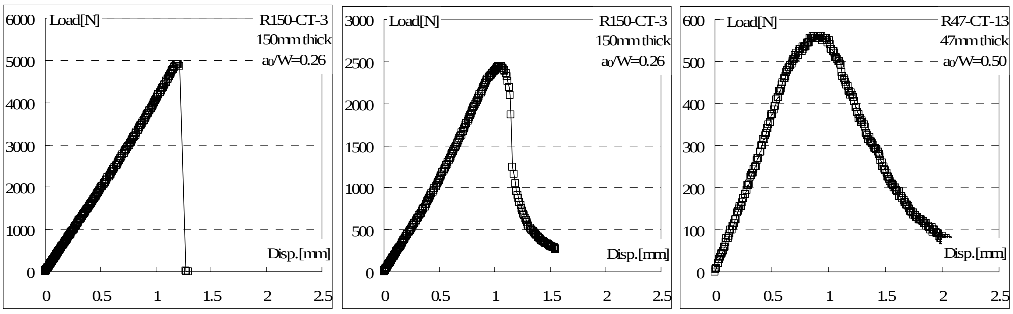

Fig.3 examples of load and displacement to each fracture feature
(Left :Brittle, Center :not-Brittle, Right :Ductile)

Fig.4, 5, 6 shows the relationship with load-displacement relation and Fig.7 shows the distribution of the maximum-load of the all specimens. And the marks with “O” and “X” were in Fig.4, 5, 6, and they indicated crack initiated point on the right or left surfaces of each specimen. For the specimens fractured in brittle, both-sides cracks started at the same time. On other sides for the specimens fracture in ductile and not-brittle, both side cracks didn’t start to propagate at once or in parallel. In this study, we didn’t define the differentiation with its annual rings and crack-initiation behavior. And so we calculate the ratio the load crack-initiated-load to the maximum load ($P_{ini.}$ /Pmax). As shown in table 1, 2, 3, for many specimens the ratios were over 0.8, some were 1.0. These ratios are based on the results from the observation of its surfaces, are not including the interior of the woods. Additionally, we didn’t take an account of bridging effect. For the crack initiation problem, Yoshihara et al [2] used 5%-off-set method to define

crack initiation on CT tests, and Ian et al [3] reported that crack started at the maximum load on DCB tests. In these repots, they used hemlock. Through those reports and our results, it is appropriate to define that crack-initiation-point of general-structural-timber is at that maximum, we thought.
The fracture characteristics of all specimens were on table 1, 2, 3. In these tables Brittle fracture is indicated in **bold**, not-Brittle is indicated in ***bold + italic*** and ductile is indicated in normal font. For example, in the case that $a_0/W=0.25$, Scots pine and width =150mm, there were three different fracture characteristics. As mentioned above, bridging effect or the effect of shear deformation or some factors affected to change of fracture types. Through our results, if the width is under 94 and a_0/W is over 0.50, all specimen's fracture characteristic is in ductile. So we can get stable Mode 1 fracture toughness from CT tests under that specimen's size, we thought. With the three point bending tests with notched beams, Gustafsson[4] suggested that its width is 45mm and a_0/W is 0.6 for Mode 1 fracture toughness. So there might be close tendency of the range of geometry with three-bending-tests and CT tests.
Through above results, with the date until the maximum load, we tried to calculate the fracture toughness J_{1C}.

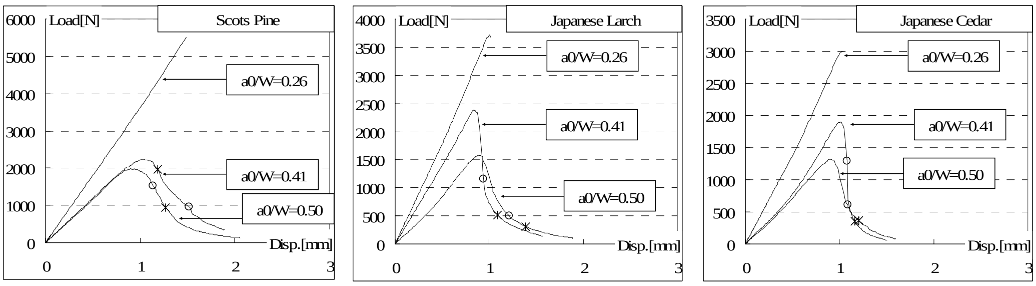

Fig.4 crack initiation point on load and displacement (B=150mm)

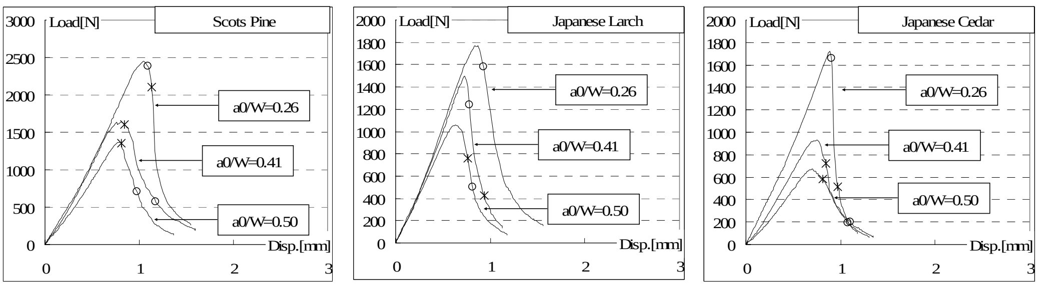

Fig.5 crack initiation point on load and displacement (B=94mm)

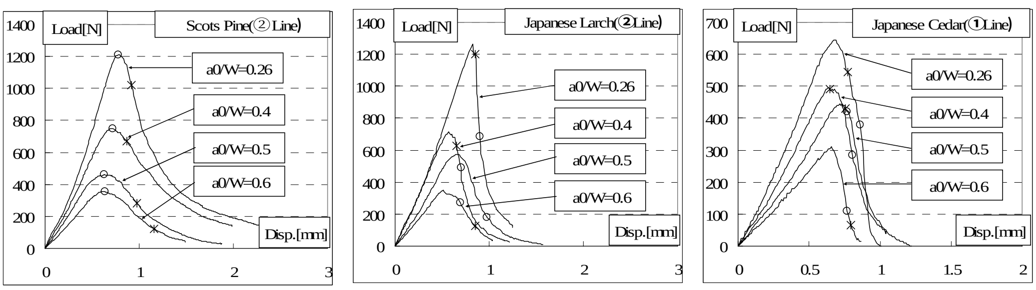

Fig.6 crack initiation point on load and displacement (B=47mm)

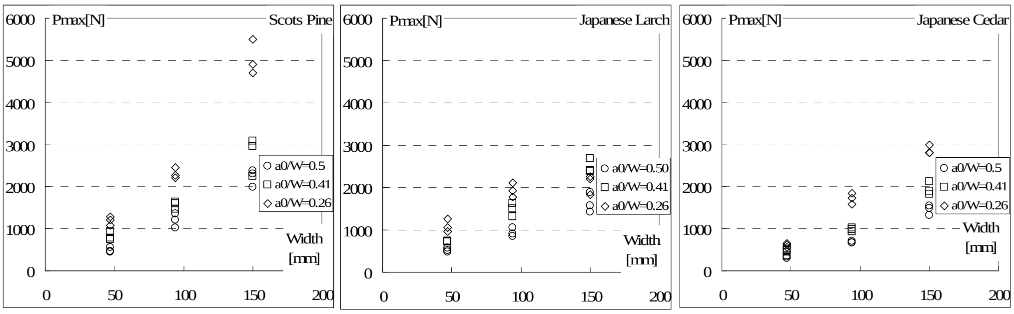

Fig.7 the maximum load of all specimens

3.2 calculation of J-integral

Mode 1 J-integral for crack initiation, J_{1C}, was calculated by Eq.1) proposed by Merkle and Corten [5] and results are in Fig.8. This equation is appeared on the JSME S001 [1] for crack initiation with metal materials. In this standard, the dimensionless-crack length defined from 0.5 to 0.75, this range is indicated in those diagrams. Additionally other researcher's results are on the same ones too. They are the results from CT tests by Yoshihara et al [2], DCB tests reported by Ian et al [3], three-pointed bending tests by Daudeville and Yasumura [6]. As shown in Fig.8, in the case the dimensionless-crack-length is small, the J_{1C} is high. The longer the crack length is, the smaller the J_{1C} are. In the case dimensionless-crack-length are 0.5 or 0.6, our results are getting stable and similar to the reported values. The results with Scots pine and Japanese larch are similar, but J_{1C} obtained from Japanese cedar was almost constant. This is affected with its Young's module or shear module, we thought. However if the dimensionless-crack-length is over 0.5 and its thickness is under 94mm, we can get J_{1C} value similar to the past study from CT tests with Eq.1) .

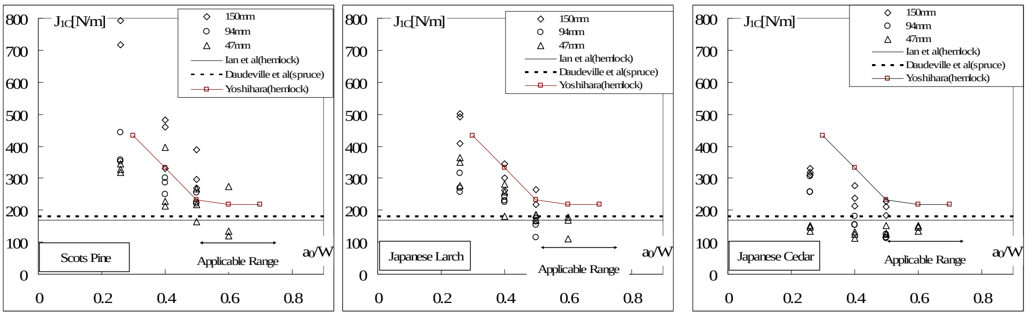

Fig.8 the distribution of J-integral for all specimens
(Left : Scots pine, Center : Japanese larch, Right: Japanese cedar)

$$J_{1C} = \frac{A}{B * b_0} * f\left(\frac{a_0}{W}\right) \quad \ldots \text{Eq.1)}$$

where,

$$f\left(\frac{a_0}{W}\right) = \left(2\frac{1+\beta}{1+\beta^2}\right), \quad \beta = \left(\left(\frac{2a_0}{b_0}\right)2 + \left(\frac{2a_0}{b_0}\right) + 2\right)^{1/2} - \left(\frac{2a_0}{b_0} + 1\right)$$

a_0: initial crack length, W: specimens length (shown in Fig.1), b_0: W-a_0, B: width
A: the area with load and loading-point-displacement (up to the maximum load)

Table 1 Fracture characteristic and fracture toughness with Scots pine

	a_0/W	thickness [mm]														
		150					94					47				
		Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]
Scots Pine	0.26	Brittle	5490	5490	1.00	888	Ductile	2385	2445	0.98	444	Ductile	1065	1080	0.99	329
		Ductile	4230	4700	0.90	718	Ductile	2130	2205	0.97	356	Ductile	1210	1210	1.00	317
		notBrittle	5030	5040	0.99	793	Ductile	2235	2265	0.99	352	notBrittle	1020	1275	0.80	344
	0.41	Ductile	1955	2240	0.87	331	Ductile	1600	1640	0.98	300	Ductile	790	935	0.84	396
		Ductile	2135	2945	0.72	459	Ductile	1595	1595	1.00	287	Ductile	745	750	0.99	227
		Ductile	2405	3090	0.78	481	Ductile	1465	1470	0.99	249	Ductile	765	775	0.99	213
	0.50	Ductile	1530	1985	0.77	297	Ductile	1355	1365	0.99	255	Ductile	520	560	0.93	267
		Ductile	1590	2385	0.67	389	Ductile	585	1205	0.49	219	Ductile	455	460	0.99	164
		Ductile	1540	2305	0.67	270	Ductile	960	1020	0.94	184	Ductile	450	455	0.99	218
	0.60	-					-					Ductile	285	400	0.71	273
												Ductile	355	355	1.00	134
												Ductile	270	305	0.89	120

Table 2 Fracture characteristic and fracture toughness with Japanese larch

	a_0/W	thickness [mm]														
		150					94					47				
		Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J1C[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]
Japanese Larch	0.26	Brittle	3720	3720	1.00	408	Ductile	1580	1770	0.89	257	Ductile	835	1055	0.79	364
		Brittle	4140	4140	1.00	501	notBrittle	2040	2100	0.97	316	notBrittle	1200	1265	0.95	349
		Brittle	4080	4080	1.00	491	Ductile	1545	1920	0.80	226	Ductile	895	960	0.93	277
	0.41	notBrittle	1155	2390	0.48	262	notBrittle	1240	1500	0.83	230	notBrittle	695	745	0.93	257
		Brittle	2690	2690	1.00	346	notBrittle	695	1630	0.43	242	notBrittle	625	715	0.87	180
		notBrittle	535	2410	0.22	300	notBrittle	1130	1323	0.85	226	Ductile	675	720	0.94	282
	0.50	Ductile	495	1580	0.31	218	Ductile	760	1060	0.72	164	Ductile	445	485	0.92	168
		Ductile	525	1880	0.28	265	Ductile	540	915	0.59	114	Ductile	180	575	0.31	186
		Ductile	320	1435	0.22	175	Ductile	770	855	0.90	153	Ductile	430	515	0.83	186
	0.60	-					-					Ductile	250	350	0.71	170
												Ductile	270	350	0.77	111
												Ductile	165	380	0.43	178

Table 3 Fracture characteristic and fracture toughness with Japanese cedar

	a_0/W	thickness [mm]														
		150					94					47				
		Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]	Features	$P_{ini.}$[N]	Pmax[N]	$P_{ini.}$/Pmax	J_{1C}[N/m]
Japanese Cedar	0.26	Brittle	2810	2810	1.00	310	notBrittle	1665	1725	0.97	257	Ductile	545	645	0.84	152
		Brittle	2790	2800	0.99	319	notBrittle	1560	1580	0.99	258	Ductile	535	610	0.88	134
		Brittle	2995	2995	1.00	331	Brittle	1845	1845	1.00	305	Ductile	490	656	0.75	148
	0.41	Brittle	1295	1900	0.68	237	notBrittle	720	930	0.77	153	Ductile	490	495	0.99	131
		Brittle	2115	2125	0.99	276	Brittle	950	980	0.97	155	Ductile	435	475	0.92	113
		notBrittle	1495	1815	0.82	213	Ductile	1008	1028	0.98	180	Ductile	305	370	0.82	124
	0.50	Brittle	1310	1550	0.85	228	Ductile	580	675	0.86	115	Ductile	430	445	0.97	152
		Ductile	605	1320	0.46	183	Ductile	380	670	0.57	112	Ductile	305	340	0.90	124
		Ductile	415	1490	0.28	210	Ductile	635	710	0.89	125	Ductile	70	300	0.23	128
	0.60	-					-					Ductile	110	310	0.35	123
												Ductile	65	250	0.26	101
												Ductile	65	180	0.36	86

4. Conclusion

In this study, to obtain the fracture toughness J_{1C} and understand fracture feature of wood, we conducted CT tests with some structural glue-laminated timber. The parameters were width of specimens, initial crack length and wood species. Through observation of crack behavior and calculation of J_{1C}, we understood followings:

1) We analyzed the fracture features influenced with width, initial crack length and wood species on CT tests. It is appropriate to consider that crack initiation is at the maximum load for structural glulams. This aptitude is similar to the past reports. It was reconfirmed that determination of cracks-propagation is so difficult.
2) Based on above results, we calculated J_{1C} with the equation by Merkle and Corten. If the dimensionless-crack-length is over 0.5 and the width is under 94mm, we can get stable Mode 1 J_{1C}. And these values are close to some past study from other type tests

Reference

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