Effect of manufacturing on the quality of rounded dovetail joints

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ABSTRACT

The paper discusses manufacturing parameters that affect the quality of Rounded Dovetail Joints (RDJ's). RDJ's are a versatile connection concept with a complex load transfer mechanism governed by its geometric features which in turn are influenced by manufacturing parameters. The effects of different climatic conditions and manufacturing tolerances on the structural performance of RDJ's produced from western hemlock (*Tsuga heterophylla*) were studied under vertical shear loading. The joint capacity, load at 3 mm relative vertical deformation, and maximum deformations were evaluated using analysis of variance. It was found that the specimens manufactured and tested with low and constant moisture content outperformed the specimens evaluated under other climatic conditions. It was also determined that the joints produced at low machining speed and therefore high cutting quality have better structural performance than those produced at higher speed. The paper demonstrates that manufacturing parameters have an impact on the quality and structural performance of RDJ's and that the advantageous load carrying mechanism of RDJ's requires dried timber and precise manufacturing methods.

INTRODUCTION

Until the mid-20th century, carpentry wood-to-wood joints were commonly used in construction with their manufacturing based on the experience of skilled wood workers. High labour costs, requirement of high degree of workmanship, assembly difficulties, and inefficient use due to over dimensioning made these joints too expensive. Recent developments in wood processing machines have created the possibility of producing these joints cost effectively. The Rounded Dovetail Joint (RDJ) and the Double Rounded Dovetail Joint (DRDJ) are relatively new concepts adapted for production with a CNC-timber processor. A number of experimental studies on RDJ provided valuable insight into the structural performance of this versatile connection (Kreuzinger and Spengler 1999; Hochstrate 2000; Bobacz 2002, Tannert et al. 2007).

Joints are arguably the most important part in any structural timber system governing their serviceability and durability performance (Snow et al. 2006). The performance of timber joints is affected by the manufacturing quality and the moisture content (MC) of the timber members amongst other factors such as wood species and the existence of defects in the wood. Wood-to-wood joints rely on interlocking of their form to provide stiffness and strength. Therefore it is essential to have accurately cut components (Erman 2002). Wood shrinks and swells if exposed to moisture fluctuations below the fibre saturation point. This characteristic becomes important when the MC of the timber at the time of manufacturing differs significantly from the MC of the timber under service conditions; e.g. structures constructed with green timbers that dry while in service may experience the loosening of originally tight joinery over time. Moisture gradients have been shown to affect the capacity of curved glue-laminated beams. The capacity of beams in a moistening phase is almost halved compared to the mean value of seasoned specimen and beams subjected to climate change display larger variability in capacity than seasoned specimens (Jönsson and Thelandersson 2005).

Although timber structures are exposed to various climatic conditions, in most cases the strength and stiffness properties of joints are evaluated from results of test specimens conditioned to a standard condition (Nakajima 2000). The performance of the joints of these structures should be properly evaluated according to the conditions in which they are used. Manufacturing tolerances can significantly impact the performance of joints. Therefore, reducing the variations in geometry and improving the quality of workmanship directly affects connection performance. Reducing the variability in the manufacturing process, CNC-processing technology provides repetitive, identical, very accurate and precise joint geometry. The individual set-up and the service condition of the processing machine and tooling, however, may affect the cut-quality and geometry, hence, the connection performance.

In previous studies at the University of British Columbia was proven that excellent tight fitting RDJ can be produced, however, the issue of lack of fit resulting from drying of the timber after manufacturing was also encountered. No research on the influence of seasoning on the structural performance of RDJ under load has been done, neither has the effect of manufacturing parameters been studied previously although known to be of vital importance. This work explores the influence of moisture content fluctuations and tolerances on the structural performance of RDJ and DRDJ under static shear loading.

EXPERIMENTAL DESIGN

Four climatic conditioning situations with practical relevance are examined. These are: DD - specimen dry at manufacturing and tested with low MC, DWD - specimen dry at manufacturing, subjected to high humidity, then dried and tested with low MC, WD - specimen subjected to high humidity, wet at manufacturing, then dried and tested with low MC, and WW - specimen wet at manufacturing and tested with high MC. The DD conditioning simulates the desired case of timber processed and used in dry condition. The DWD conditioning simulates a case where dry timber is cut, but then stored or transported in a wet climate, and dried again before being used in a building. The WD conditioning simulates the process of cutting timber with high MC that then dries inside the erected building. The WW conditioning occurs when green timber is processed, and loaded in a structure while it is still green.

The experimental layout for climatic conditions study is a two-way analysis of variance. One factor is the conditioning with four levels (control and three variations) and the second factor is the dovetail configuration with two levels (single and double dovetail). A total of 50 specimens (consisting of main beam and joist) were used in the tests, 10 for the control test series and 5 for each of the variations for both the single and double dovetail configuration.

Four additional tolerance situations are examined: specimens with the tenon 1 and 2 mm smaller than the mortise on each side of the dovetail flange, and specimens produced using medium and high machine processing speed. These test series are compared to the control - low machine cutting speed and with tight fitting joint. The experimental layout for the tolerances study conditions study is a one-way analysis of variance comparing four different tolerance conditions to the control. 20 specimens were used in the manufacturing tolerances tests. Five specimens each were manufactured with a 1-mm gap, a 2-mm gap, at medium and at high speed.

MATERIAL

Western Hemlock (*Tsuga heterophylla*) was used in the study. The moisture content (MC) and the apparent density (based on specimen as tested weight and volume) of each specimen were determined before testing. Table 1 summarizes the material properties.

Table 1: Summary of material properties; average values and standard deviations in ()

	Moisture Content (%)				Apparent Density (kg/m^3)			
	Main beam		Joist		Main beam		Joist	
Control RDJ	12.9	(1.2)	12.3	(1.5)	474	(32)	498	(39)
Control DRDJ	13.7	(1.5)	11.7	(0.4)	512	(44)	441	(27)
DWD RDJ	11.0	(0.3)	12.2	(1.2)	421	(26)	482	(48)
DWD DRDJ	11.3	(0.5)	12.2	(0.6)	479	(14)	526	(58)
WD RDJ	10.8	(0.2)	11.6	(0.2)	450	(30)	463	(38)
WD DRDJ	11.2	(0.2)	11.5	(0.2)	445	(9)	444	(10)
WW RDJ	23.4	(3.3)	21.8	(1.2)	539	(57)	497	(58)
WW DRDJ	22.7	(2.1)	21.9	(1.5)	572	(48)	504	(47)
S5 RDJ	14.9	(1.5)	14.8	(2.2)	465	(17)	466	(20)
S9 RDJ	15.3	(1.5)	14.5	(1.6)	481	(30)	456	(19)
G1 RDJ	15.9	(1.8)	14.4	(2.3)	491	(41)	419	(9)
G2 RDJ	14.3	(1.9)	13.5	(0.5)	521	(27)	444	(18)

The RDJ was applied to connect a joist to a main beam. The member width and height were chosen as 89 mm x 184 mm, respectively. Vertical shear loading mode was chosen with beam and joist lengths of 600 mm and 800 mm, respectively. To enable comparisons with previous studies, the dovetail geometry (Fig. 1) was chosen as: width $b_1 = 50$ mm, depth $t = 28$ mm, dovetail angle $k = 15°$, flange angle = 15° and dovetail height $h_1 = 119$ mm. For the DRDJ, the height and width of the second dovetail were $h_1 = 79$ mm and $b_2 = 57.5$ mm, respectively. The Hundegger K2-5 5-axis beam processor was used to process the specimens.

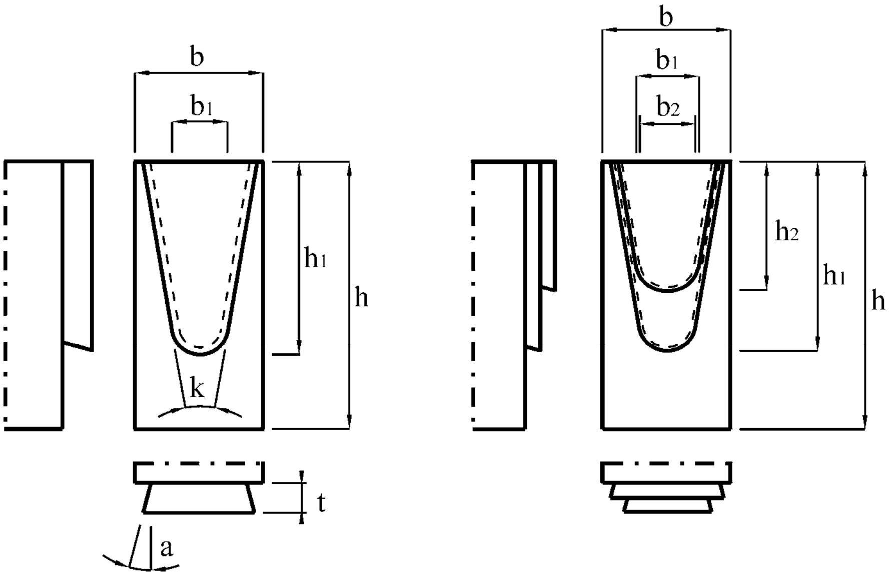

Figure 1: Geometric parameters of RDJ (left) and DRDJ (right)

METHODS

Tests were performed similar to previous research on RDJ so that the results can be compared. The test specimens were mounted on a test apparatus by supporting the main beam on two 100 mm x 100 mm x 10 mm steel plates, two other steel plates of 50 mm x 50 mm x 5 mm on the backside of the specimens prevented these from moving back (Fig. 2). The main beam was not clamped, thus allowing minor rotation about its long axis, a situation that closely simulates the supporting condition in a real structure. The free end of the joist was simply supported on a 100 mm x 100 mm x 10 mm steel plate which rested on a damper with a spring stiffness of approximately 1 kN/mm, thus simulating an approximately 4 m long beam of the given section. The load was applied at a distance of 350 mm from the joint and distributed onto the joist with a steel plate with a diameter of 100 mm and 10 mm thickness.

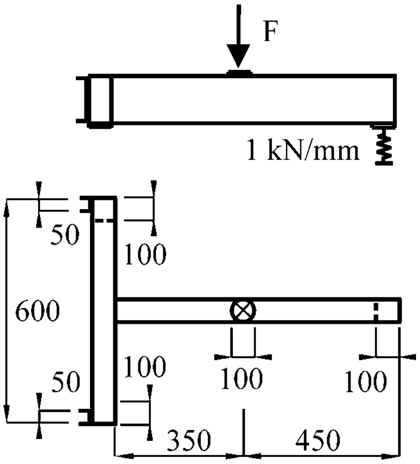

Figure 2: Test set up

The applied load from the actuator, the force at the support of the free joist end and the vertical movement on both sides of the joint (as the relative displacements between main beam and joist) were recorded. The force transmitted by the connection was calculated as the difference between the applied load and the load recorded at the free end of the joist. The vertical joint deflection was calculated as the average between the vertical movements of the two joint sides. The load regime was load controlled. One dummy specimen was used to estimate the capacity and set the rate of loading for the following tests to ensure that failure of the connection occurred after approximately six minutes, in accordance to EN 26891 (1991).

The maximum force applied (F_{ult}) represents the connection capacity. Its 5th percentile can be used to determine the design load for the strength limit state. It is important to consider a deformation limit of the joint in order to prevent unacceptable non-structural damages of the surrounding structure. In this study, a 3 mm limit for the relative vertical deformation between main beam and joist was used and the load at 3 mm deformation ($F_{@3mm}$) was determined. $F_{@3mm}$ can be considered the design load for the serviceability limit state.

RESULTS

RDJ control specimens show little initial connection slack due to alignment issues. The load increases linearly until reaching deformations of approximately 3 mm. At that point a load is reached that leads to crack development. A load redistribution process initiates and stable crack development is observed. Further increases in load are associated with bigger increases in deformation until brittle failure occurs at capacity. DRDJ control specimens do not show any initial slack. The load-deformation curve is almost tri-linear. The load increases at the beginning of the actuator movement and linear behaviour occurs until reaching a deformation of approximately 1 mm. Then the curve flattens until reaching a deformation of approximately 4 mm. After this point the connection tends to stiffen until reaching capacity. The load deformation response curves for the control specimens are shown in Fig. 3.

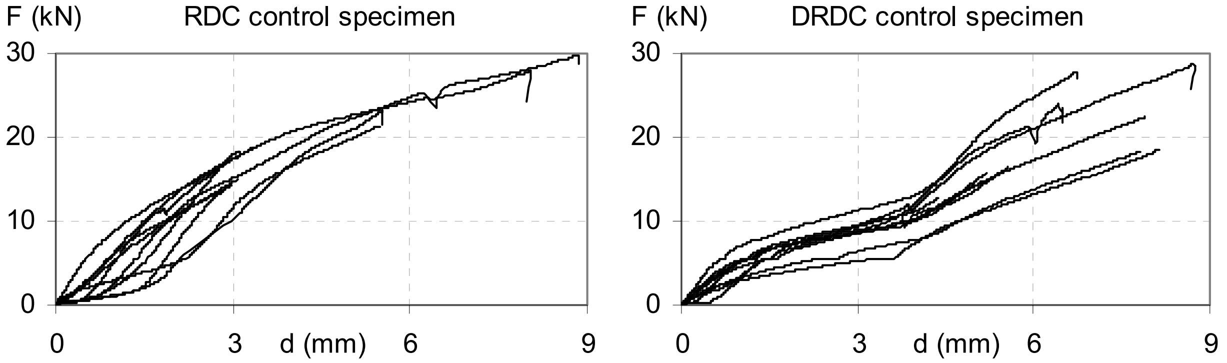

Figure 3: Load deformation response (shear force versus vertical joint deformation)

RDJ specimens produced and tested under varying climatic conditions vary in their initial alignment behaviour, with the WW specimens showing the highest initial alignment behaviour, while for DWD specimens the load increases right at test start. The specimens exhibit large variability in capacity and maximum deformation. DRDJ specimens produced and tested under varying climatic conditions exhibit less variability in their alignment behaviour. RDJ's produced at higher speeds do not show varied initial alignment behaviour, their load response is very similar to the control specimens but less stiff. RDJ's produced with a gap do not show initial alignment behaviour, the existing gap is closed immediately at test start.

Table 2 gives a summary of the test result with the means and standard deviations of the recorded variables: capacity (F_{ult}), the load at 3 mm deformation ($F_{@3mm}$), and the maximum deformation (d_{max}).

Table 2: Average values and standard deviations () for F_{ult}, $F_{@3mm}$, and d_{max}

Test series	F_{ult} (kN)		$F_{@3mm}$ (kN)		d_{max} (mm)	
Control RDJ	19.9	(5.6)	14.9	(2.7)	4.6	(2.3)
Control DRDJ	20.0	(5.5)	8.6	(1.7)	6.6	(1.5)
DWD RDJ	27.4	(5.1)	10.8	(4.4)	8.7	(3.1)
DWD DRDJ	20.2	(3.8)	4.2	(1.9)	9.7	(1.3)
WD RDJ	18.4	(7.1)	11.9	(1.9)	6.2	(2.7)
WD DRDJ	22.8	(3.2)	5.3	(1.4)	10.0	(1.3)
WW RDJ	20.5	(7.4)	8.4	(3.3)	9.0	(2.4)
WW DRDJ	21.9	(5.2)	8.8	(1.3)	9.2	(2.8)
S5 RDJ	18.1	(2.5)	11.6	(3.3)	5.2	(1.0)
S9 RDJ	18.8	(5.0)	7.9	(5.9)	6.1	(2.0)
G1 RDJ	20.3	(9.5)	11.7	(0.2)	8.2	(5.0)
G2 RDJ	15.9	(4.7)	10.1	(0.8)	8.1	(4.5)

ANALYSIS

F_{ult}, $F_{@3mm}$, and d_{max} of the connection under shear load were analyzed using analysis of variance (ANOVA). The purpose of ANOVA is to test differences in means of experimentally obtained values for statistical significance. The significance of a result is also called its p-value which is compared to a significance level α. In the presented study, the level is $\alpha=0.05$ and results that yield $p<0.05$ are considered significant. Table 3 gives a summary of the ANOVA comparing the climatic conditionings and tolerances to the control, as well as RDJ and DRDJ.

Different climatic conditions have no significant effect on F_{ult} and neither has the dovetail configuration. For $F_{@3mm}$, the interaction between conditioning and dovetail is statistically significant. Therefore the factors cannot be interpreted separately. However, the specimens manufactured and tested in dry condition displayed a higher load than those exposed to varying climatic conditions and RDJ specimens a higher load deformation than DRDJ. Regarding d_{max} both dovetail type and conditioning have a significant effect. DRDJ reach larger deformations compared to RDJ and the joints manufactured and tested in dry condition exhibit a lower d_{max} compared to those exposed to the variable climatic conditions. Tolerances do not affect F_{ult} of the joints, but $F_{@3mm}$, where the design load of the control specimens, on average, 45% higher. Finally, the effect of tolerances on d_{max} is not significant.

Table 3: Summary of ANOVA

Tested variable	Study of climate conditions			Study of tolerances
	p-value Interaction	p-value Conditioning	p-value Dovetail	p-value
F_{ult} (kN)	0.134	0.350	0.819	0.736
$F_{@3mm}$ (kN)	0.005	<0.001	<0.001	0.006
d_{max} (mm)	0.292	<0.001	0.010	0.168

DISCUSSION AND CONCLUSION

The presented work reduces the existing knowledge gap regarding the structural performance of RDJ's. RDJ specimens perform almost linear throughout the load deformation curve until reaching a deformation that leads to crack development. They show initial connection slack due to alignment issues resulting in variability of initial stiffness. DRDJ in contrast show less variability in capacity and little initial connection slack since the first dovetail has immediate connection contact. The load-deformation curve is almost tri-linear. The low stiffness of the middle part of the curve can possibly be attributed to connection inaccuracies with the second dovetail not completely participating in the load bearing process.

Changes of MC caused by varying climatic conditions have a significant effect on loads at 3 mm deformation and in consequence on the performance under serviceability considerations. Specimens subjected to different climatic conditions exhibited a lower load at 3 mm deformation and showed larger maximum deformations than those manufactured and tested in the dry condition. Joint tolerances do affect the structural performance of RDJ. Specimens produced at low speed and with no gap have higher load at 3 mm deformation. Low cutting speed produces a clean cut and good fit joint, whereas high cutting speed causes vibration of the machine resulting in reduced connection.

Based on the results presented in this study, the authors recommend that RDJ be manufactured using dry timber and ensure no significant changes in MC take place. It is also proposed that the joints be produced at low speed when using a CNC timber processor to ensure a good quality and good fit joint, resulting in a better structural performance.

Given the scope of the presented work, the authors cannot comment on whether RDJ are appropriate to resist seismic loads under reverse loading conditions or long-term loading. The authors recommend to further study applications of RDJ to establish amongst other factors the process of creep during concurrent moisture changes.

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