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EXPERIMENTAL DETERMINATION OF R CURVES FOR EUROPEAN SPRUCE USING DCB TESTS

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ABSTRACT: This paper presents an experimental procedure for obtaining the fracture resistance (R curve) of solid wood specimens made of spruce. Double Cantilever Beam (DCB) tests were performed in order to determine energy release rate vs crack length in Mode I wood fracture (crack opening). Ten wood specimens were loaded using the Universal Testing Machine and force-displacement curves were recorded. The most important parameter - crack length was monitored as the crack propagates using Digital Image Correlation (DIC) method. In order to obtain accurate R curve results, procedure which includes calculating cumulative released energy was employed. The cohesive energy G_f was determined based on the R curves. These results can further be analysed in order to obtain cohesive law for Mode I fracture of wood.

KEYWORDS: Mode I fracture, wood, DCB, DIC, R curve

1 INTRODUCTION

Sustainability, renewability and circularity have become great concerns for today's society. Since the construction industry represents one of the biggest sectorial emitters of greenhouse gases causing anthropogenic climate change, application of sustainable and/or natural materials for buildings is advisable as a significant mitigation measure. Aside from its aesthetic appeal, wood represents an eco-friendly material with a significant potential for civil engineering. In order for wood to be implemented correctly for structural purposes, its mechanical behaviour has to be defined for different stress states that can appear in the design process.

Often, timber beam's height needs to be reduced at the supports (notched) so as to satisfy different structural and architectural requirements. Notches represent potentially weak spots in timber structural elements, as stress concentration occurs at the notch corner, decreasing the overall load-carrying capacity. In order to determine possibilities for strengthening and adequate design procedures, comprehensive research has been performed on end-notched timber beams [1]. The research results have proved that a dominant failure mechanism of unreinforced end-notched beams is Mode I fracture - crack opening (Figure 1) caused by excessive tensile stress perpendicular to grain of timber with unstable crack propagation. The unreinforced end-notched have experienced a considerably reduced load-carrying capacity compared to the expected load-carrying capacity of the beams without notches. In order to accurately describe the behaviour of end-notched timber beams, it is necessary to determine Mode I fracture parameters. Therefore, cohesive law for Mode I fracture of wood is necessary for adequate analysis of stress state around the notch area.

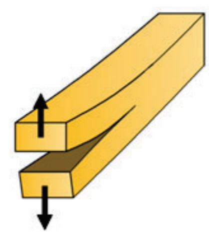

Figure 1: *Mode I fracture – crack opening*

Cohesive law for Mode I fracture can be determined based on the analysis of damage process zone which develops in wood in the case of propagating cracks. Development of the damage process zone causes toughness to change as the crack propagates, which is characteristic of many materials including wood. Process zone development in wood is a direct consequence of fibre-bridging effect (unbroken fibres connect the crack surfaces and slow down the crack growth).

Crack propagation experiments in materials which develop fibre bridging across the crack start with a machined notch that has no process zone [2]. As the load is applied fibre-bridging zone develops with two crack tips. One crack tip is the actual crack tip and one is at the edge of the fibre-bridging zone defined as the notch root, with the distance between them representing the process zone length (Figure 2). At the initial point of fracture, the crack tip moves while the notch root remains stationery

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and toughness is low. As the process zone develops, since unbroken wood fibres that connect crack surfaces can carry load, toughness tends to raise with crack growth. Once the connecting fibres break, the process zone length stabilizes (steady-state crack propagation). Onward, the process zone propagates together with the developing crack, and the toughness becomes constant. The fracture resistance curve (R curve) is a representation of Mode I fracture toughness of the material in relation to crack propagation. In order to correctly describe the fracture process of any material, including wood, an accurate definition of the R curve is necessary. In accordance with the explained process zone mechanism, the R curve starts at a minimum initial value (corresponding to the low toughness) and then rises with the development of fibre-bridging zone. Once steady-state crack propagation is reached, the R curve becomes constant (corresponding to the constant toughness). The plateau of R-curve represents the cohesive energy - G_f.

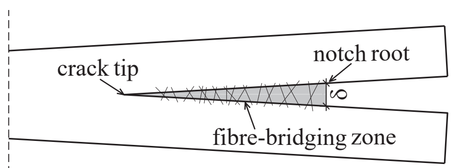

Figure 2: *Crack tip region with fibre-bridging zone*

In order to determine Mode I fracture properties of wood, different methods have been used so far by the researchers. Testing procedures included: three-point bending test [3,4], single-edge-notch specimen [5], wedge-splitting test [6-8], tapered double cantilever beam test [9,10], and double cantilever beam test [11-13]. The single-edge-notch specimen and wedge-splitting test represent standard geometries for determination of fracture energy for wooden products employed in timber engineering. On the other hand, the double cantilever beam test and tapered double cantilever beam test geometries are mostly used in different scientific research activities [14].

In this paper an experimental procedure for determining the fracture resistance curve of wood is explained. Double cantilever beam (DCB) tests were performed in order to determine Mode I fracture (crack opening) properties of spruce wood. As wood represents an orthotropic material, the fracture behaviour of wood is orientation-specific. Hence, six different material fracture planes can be defined - LR, LT, RL, RT, TL, TR (Figure 3), where the first letter indicates the direction perpendicular to the crack plane, and the second letter indicates the direction of crack propagation. The letters L, R and T represent longitudinal, radial and tangential direction of the fibres, respectively. In accordance with the large-scale experiments performed on the end-notched beams crack propagation is considered in the radial-longitudinal direction - RL direction. In order to overcome the main obstacle occurring with the DCB tests, which is crack length measurement, Digital Image Correlation (DIC) method was applied for recording the crack opening and propagation. Jamaaoui et al. [15] demonstrated that DIC method can be successfully used to estimate the crack length and the mechanical state at the crack tip. R curves were obtained from the slope of cumulative energy - crack length curve. The cohesive energy G_f was determined from the R curves. Based on these results, cohesive law for Mode I fracture can be defined.

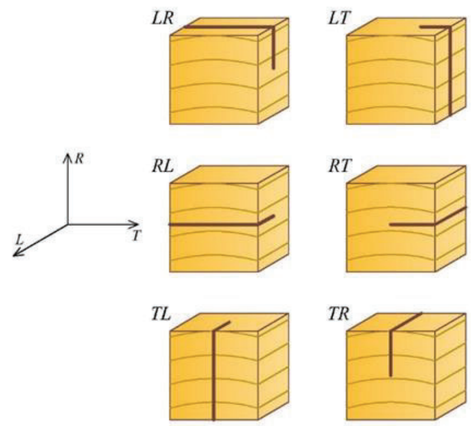

Figure 3: *Fracture planes in wood*

2 MATERIALS AND METHODS

2.1 TEST SET-UP

Altogether ten specimens made from European spruce (Picea Abies) were tested as DCB to the point of failure at the TU Delft, Faculty of Civil Engineering and Geosciences, Department of Engineering Structures. The specimens were made from spruce timber classified in the strength class C22 according to the standard EN 338 [16]. The specimens were made out of the same wood as were the large-scale end-notched beams tested previously, so that the results could be used in further numerical analysis of Mode I fracture.

DCB test set-up and specimen geometry are presented in Figure 4. The specimens' cross section dimensions were 20 x 30 mm and length was 300 mm. They were denoted as S1-S10. The initial 100 mm long crack was formed using a saw with 1 mm thickness. Steel pins with a diameter of 3 mm were used for joining the specimens to the loading fixture.

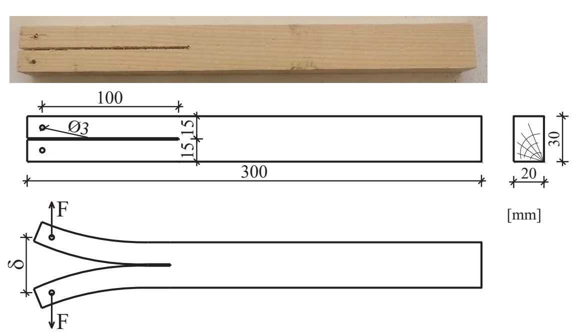

Figure 4: *DCB test set-up and specimen geometry*

Universal testing machine UTM-25 was employed for the experimental testing (Figure 5). Load was applied monotonically with a displacement-controlled rate of 5 mm/min. Load and displacement were recorded using the loading cell with a frequency of 2 Hz. All tests were performed under ambient conditions (at a temperature of about T = 20º C and a relative humidity of about RH = 65%). Using a digital hygrometer moisture content was measured in all the specimens and it had values in a range of 11.0% to 11.9%.

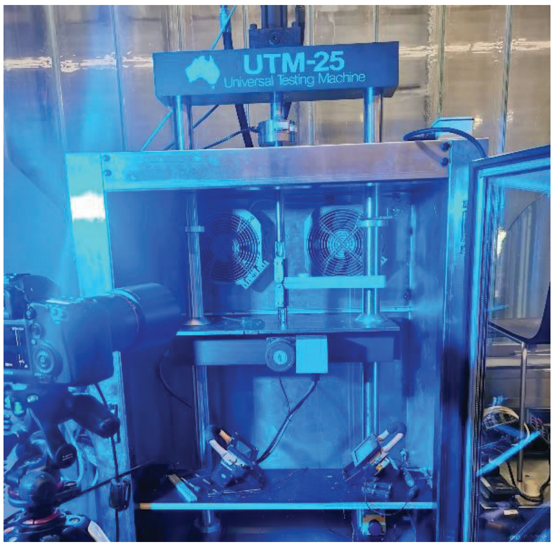

Figure 5: *Experimental set-up*

DIC method was employed for crack length measurement, as well as the measurement of crack opening during the testing. The main problem of this experiment is accurate crack length reading which is necessary for the correct definition of R curves. To overcome this problem, images recorded with a camera were analysed with GOM correlate software. By defining two curves on the upper and lower crack surfaces which are easily visible during the analysis, and measuring the separation between these curves allowed for the accurate crack length reading at each loading step.

2.2 PROCEDURE FOR ENERGY RELEASE RATE

The force-displacement curves recorded during the experimental research were used to obtain R curves (energy release rate vs crack length) based on the procedure explained in the paper by Wilson et al. [17]. This approach can be applied only to fracture mechanics tests with elastic materials (such as European spruce). In elastic materials, the fracture energy is released only due to the development of the damage process zone and the crack growth in the crack plane. For these materials no energy is released due to the non-linear (plastic or damage) behaviour of the materials surrounding the crack plane. Procedure consists of calculating the cumulative energy released up to the certain value of the loading point displacement δ (presented as shaded area in Figure 6). In order to determine cumulative energy, unloading from this point would be required. As Wilson et al. [17] argue in their paper, the fibre-bridging zone would interfere with the unloading and the curve would not return to the origin. Furthermore, authors explain that energy from such crack plane interference during unloading is not a part of the energy released during monotonic crack propagation, and it should not be a part of the cumulative released energy. Therefore, the proposed method assumes that the unloading would return to the origin displacement - δ_0. As suggested, cumulative released energy can be calculated as in accordance with the following expression:

$$U(\delta) = \int_{\delta_0}^{\delta} F(x)dx - \frac{1}{2}F(\delta)(\delta - \delta_0) \quad (1)$$

where U = cumulative energy, δ = displacement, δ_0 = origin displacement and F = force.

Afterwards, cumulative energy is cross-plot in the function of the corresponding crack length (Figure 6). Crack lengths were read from the DIC images for the corresponding force and displacement during the experimental testing. Finally, the R curves represent the slope of cumulative energy - crack length curve, calculated as follows:

$$R = \frac{1}{b}\frac{dU(a)}{da} \quad (2)$$

where R = energy release rate, b = specimen width and a = crack length.

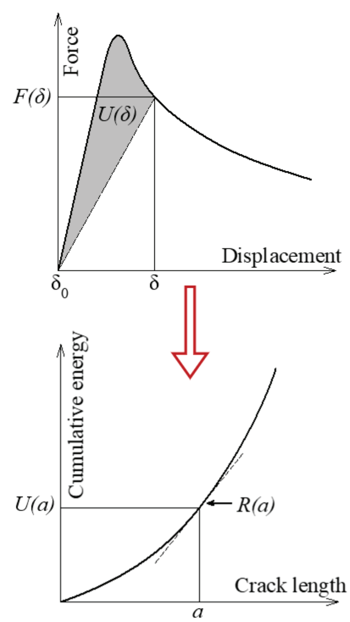

Figure 6: *Procedure for determining R curves based on cumulative released energy [15]*

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3 RESULTS AND DISCUSSION

All tested specimens experienced the expected Mode I fracture - crack opening, caused by excessive tensile stress perpendicular to the grain of wood. Typical failure mechanism of tested specimens is presented in Figure 7. Force - displacement curves of all ten tested specimens are presented in Figure 8. As it can be seen from the curves, behaviour of the specimens was entirely linear until ultimate load corresponding to the initial crack opening was reached, with a sudden drop in load at this point. Afterwards, crack propagation and its growth led to a complete separation of the specimens in two parts, with generally clear and straight surfaces between two separated parts. Crack paths followed fibre directions, with minor exceptions in the case of existing defects in wood.

Figure 7: *Typical Mode I failure mechanism of tested specimens*

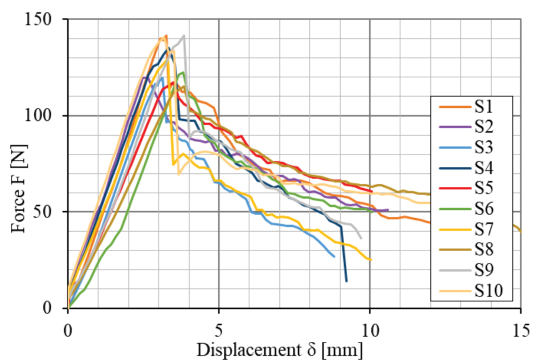

Figure 8: *Force-displacement curves*

After implementing the previously described procedure for energy release rate, cumulative energy vs crack length was calculated from the Equation (1) and presented in Figure 9. Based on these curves, using the Equation (2), R curves of tested specimens were calculated and presented in Figure 10. The recorded data of force - displacement was comprehensive enough to be easily integrated. For each step of loading, corresponding crack length was read from the DIC images analysed with GOM correlate software. Differentiation of the cumulative energy vs crack length curves was performed by fitting them with adequate third-degree polynomial curves. Afterwards, these polynomial curves easily numerically differentiated in order to obtain respective R curves for each specimen.

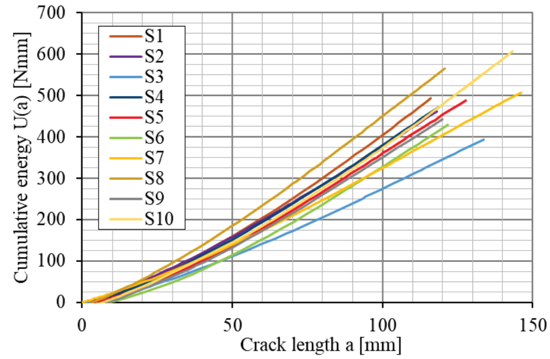

Figure 9: *Cumulative energy-crack length curves and (b) R-curves*

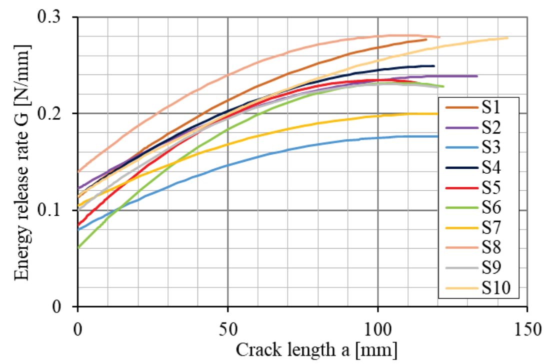

Figure 10: *R-curves*

The cohesive energy or critical value of energy release rate at propagation - G_f corresponds to the plateau value of the R curve [14]. This parameter values are estimated once the toughness stabilized after fibre-bridging process completed and R curves appear to be reaching the steady state. The experimental results for cohesive energy of tested spruce specimens are given in table 1. Cohesive energy values vary between 0.18 - 0.28 N/mm, with the mean value of 0.24 N/mm, and coefficient of variation of 13.7%.

Table 1: *The cohesive energy values*

Specimen	G_f (N/mm)
S1	0.275
S2	0.239
S3	0.181
S4	0.248
S5	0.235
S6	0.231
S7	0.200
S8	0.281
S9	0.230
S10	0.278
Average	0.236
Standard deviation	0.032
Coef. of variation (%)	13.7

The obtained cohesive energy values are comparable to the values obtained in other studies performed in order to determine fracture properties of Norway spruce. Authors Coureau et al. [14] cite cohesive energy values in the range of 0.25 - 0.31 N/mm depending on the test performed (where the value of 0.25 N/mm corresponds to the results of the DCB test). Ostapska and Malo [7] obtained mean cohesive energy value of 0.25 N/mm from the wedge splitting test. Since the results are similar to the ones obtained in this research, it can be said that the proposed procedure for determining R curves in this paper can be considered to be successful in evaluation of the cohesive energy of European spruce.

Crack opening displacement at the initial crack tip was also read from the DIC recorded images uploaded in the GOM correlate software. Crack opening displacement was determined by choosing two points at the initial crack tip, positioned at the future crack surfaces, and measuring their distance in each step as the crack opens and propagates. This parameter was necessary for further analysis in order to obtain the cohesive law for the specimens. Energy release rate plotted against crack opening displacement at the initial crack tip once it is differentiated gives the cohesive law of tested wood specimens [18]:

$$\sigma(\delta^*) = \frac{dG(\delta^*)}{d\delta^*} \tag{3}$$

where σ = nominal stress, δ* = crack opening displacement at the initial crack tip, G = energy release rate. The cohesive law for tested European spruce specimens is given in Figure 11. This was performed using the Equation (3) for an average value of the obtained R curves.

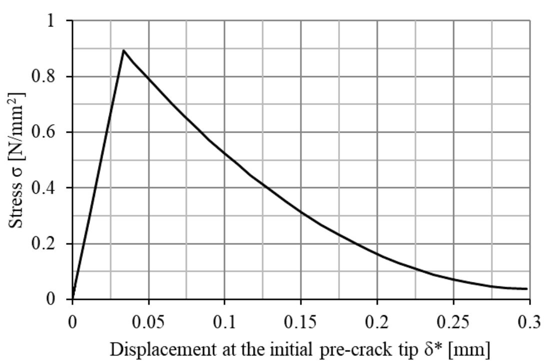

Figure 11: *Cohesive law of tested specimens*

Maximum value of nominal stress equals 0.9 N/mm^2 from the cohesive law curve and it corresponds to the value obtained by Oudjene et al. [19] also from DCB tests. Authors of the mentioned paper also successfully modelled the progressive cracking of the notch details of spruce timber beams using the parameters obtained from the DCB tests.

4 CONCLUSIONS

The condition of steady state crack propagation is required to estimate relevant fracture properties of wood. Adequate test procedure and recording are necessary in order to obtain accurate behaviour of wood in Mode I fracture (crack opening). Comprehending fracture in timber allows to determine the expected behaviour of timber structural elements in terms of load-carrying capacity, ductility and damage tolerance.

An efficient test and analysis procedure to obtain the Mode I fracture energy based on the double cantilever beam (DCB) tests is proposed in this paper. The force-displacement curves recorded during the experimental research were used to obtain fracture resistance curves (R curves). Based on the obtained results, the cohesive energy corresponding to the plateau value of the R curve was determined to be 0.24 N/mm for specimens made of European spruce. Furthermore, R curves were analysed in order to determine cohesive law of wood. The described method has been proven to be successful in determination of Mode I fracture properties of wood.

Cohesive law can be further implemented in the numerical analysis of large-scale timber elements like notched beams and beams with holes. The numerical modelling, as well as the experimental research, can help in better understanding of crack initiation and crack growth phenomenon in timber structures.

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