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DETERMINATION OF CHAR RATES FOR GLULAM COLUMNS EXPOSED TO A STANDARD FIRE FOR THREE HOURS

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ABSTRACT: The fire resistance of a structural building member includes its ability to survive a specified fire without loss of its loadbearing function. For glue laminated timber columns, fire resistance is determined by either subjecting a structural member to a standard fire test or by using one of two accepted calculation methods. For wood structural members, the calculation methods rely on char rates obtained from numerous standard fire tests. The existing calculation methods are limited under United States building codes to calculating fire resistance ratings of 120 minutes or less. However, over the past decade there has been a push towards tall wood buildings and designers desire more exposed wood to be permitted in buildings. This desire, coupled with the recent adoption of code language that permits tall wood buildings up to 18 stories, has resulted in the need to determine char rates for glue laminated timber to use in the fire resistance calculations up to 180 minutes. Here we present the experimental method and initial char rate results of glue laminated columns exposed to the standard fire.

KEYWORDS: glue laminated timber, glulam, char rate, fire resistance, tall wood

1 INTRODUCTION

The availability and code acceptance of a procedure to calculate the fire-resistance ratings for mass timber beams and columns have allowed their use in fire-rated buildings. Historically, two procedures for calculating the fire ratings of exposed wood members have been accepted by the model building codes. The first method was developed by T.T. Lie in 1977 [1]. Lie's method utilizes simple algebraic equations that only need the dimensions of the beams or column and a load factor. To account for a charred outer tension layer of a glue-laminated (glulam) beam, a core lamination of the beam or column is removed, and an extra 51 mm thick outer tension layer is added. While this method has been widely accepted, it is limited to fire resistance ratings of 60 minutes or less. The 60-minute limitation is in place because the average char depth experimentally verified for wood exposed to a standard fire is 38 mm at 60 minutes [2]. The standard fire exposure is defined in documents such as ASTM E119 [3].

The second method is a mechanistic approach found within the National Design Specification for Wood Construction (NDS) [4] and is often referred to as the reduced cross-section method [5]. This approach applies to all wood structural members covered by the NDS including structural composite materials such as glulam. In this method, the engineering calculations of the ultimate load capacity are adjusted to take into consideration the reduced dimensions with time as a result of charring. This method also requires core lamination(s) of glulam beams be replaced by extra outer tension laminations. This method has been empirically verified with the standard fire exposure for up to 120 minutes.

The maximum 120-minute fire resistance rating limitation from these approved methods is largely due to that, up until now, there has not been a need to calculate longer fire resistance ratings for wood building products. Recently, a set of proposals for tall wood buildings was approved and the 2021 International Building Code will permit the use of mass timber up to 18 stories without exposed wood [6]. With the codification of tall wood buildings comes the need for 180-minute fire resistance rated structural members made from mass timber. While the current language adopted by the code does not allow elements that would be required to be 180-minute rated to be exposed, and a portion of the fire resistance rating must come from noncombustible protection, the warm aesthetic of the wood makes encapsulation of these elements' undesirable for designers. Performance-based design may allow an engineering approach to calculate the fire resistance rating, but the char rate at 180 minutes must be verified experimentally.

A majority of fire resistance and char rate research on glulam was limited to either 60- or 120-miute tests and, to the knowledge of the authors, the longest test on glulam without non-combustible protection was reported to be 147 minutes and conducted on a beam [1, 7, 8]. Fire

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testing for a duration of 180 minutes on a glulam column without noncombustible protection has not been conducted to date and limited data on the char rate past 120 minutes exists. The aim of the study is to obtain the char rate for the glulam columns that are exposed to the standard fire, within an intermediate scale furnace, for 180 minutes.

2 MATERIALS AND METHODS

2.1 MATERIALS

The glulam was supplied from a North American manufacturer, constructed with Douglas-fir (*P. menziesii*). The original dimensions (length x width) of the glulam column were 406 mm by 413 mm. Each glulam column specimen was cut to a final length of approximately 1 m. A total of three tests were conducted without external loading. Upon arrival to the lab, the columns were conditioned for a minimum of four weeks in a 21°C/50% relative humidity environmental chamber.

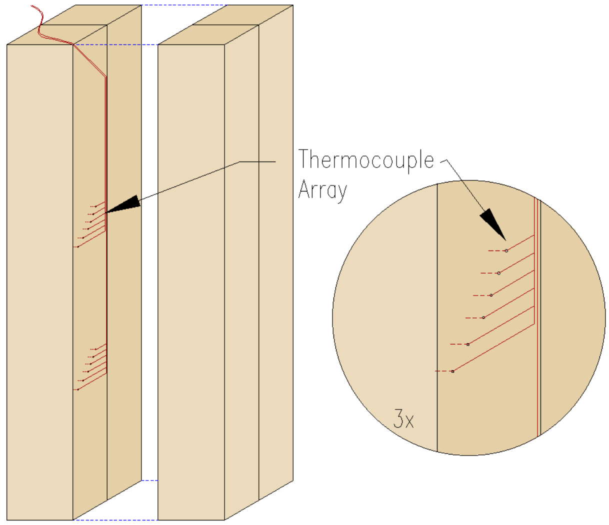

Figure 1: *Schematic of glulam column with thermocouple arrays installed on one face.*

2.2 SPECIMEN PREPARATION

To obtain the temperature profile in each specimen, thermocouples were installed (Figure 1). To install the thermocouples, the columns were first quartered longitudinally, and all surfaces were planned. Arrays of six thermocouples at 25, 52, 76, 89, 102 and 114 mm were embedded in eight locations throughout each column. The thermocouples were installed parallel to the column faces so that they were parallel with the isotherm. Two arrays were located behind each column face. The first was the lower array centred approximately 305 mm from the bottom of the column and the second, upper array, was centred approximately 610 mm from the bottom. A channel in the middle of the column was used to route the thermocouple wire out of the column. This channel allowed the thermocouples to remain protected for the duration of the 180-minute test. After installation of the thermocouples, the quarters were glued back together using a phenol resorcinol formaldehyde (PRF) adhesive. PRF was the adhesive used because it is a typical adhesive used when manufacturing glulam, it is curable at room temperature, and is resistant to high temperatures. While the adhesive cured, the columns were clamped with a pressure of 1000 kPa for eight hours. The final dimensions of the columns after being glued back together were approximately 381 mm by 381 mm (length x width). In addition to the internally installed thermocouples, one thermocouple was placed in the centre of each exposed face to estimate the start of charring. The temperatures at all 52 thermocouples were measured every 5 seconds using an automated data acquisition system.

After the thermocouples were installed and the columns were glued back together, they were returned to the conditioning room until constant mass (0.1% change) was achieved.

2.3 METHODOLOGY

2.3.1 Fire Exposure

The specimens were tested in the intermediate-scale horizontal furnace located at the USDA Forest Products Laboratory (FPL). The furnace is a metal box lined with high-temperature-resistance insulation. The interior dimensions of the furnace are 1.83 m long, 1.09 m wide and 1.27 m high. The heat source is eight diffusion-flame, natural-gas burners on the floor of the furnace. During combustion, vents at the bottom of the furnace provide air via natural draft. Four capped furnace thermocouples were located 305 mm from the top of the furnace interior and 305 mm from each fire-exposed face of the column. The gas input was controlled so the temperature of the capped thermocouples followed the standard time–temperature curve described in ASTM E119 [3].

Within the furnace, the glulam column was placed on fire bricks (Figure 2) to maintain a distance from the bottom of the furnace and the burners. A custom-designed frame was used to hold the glulam columns and included a noncombustible (ceramic batting) surround. Approximately 914 mm of the column was exposed within the furnace with 102 mm of the column projecting through the lid and not exposed to the fire.

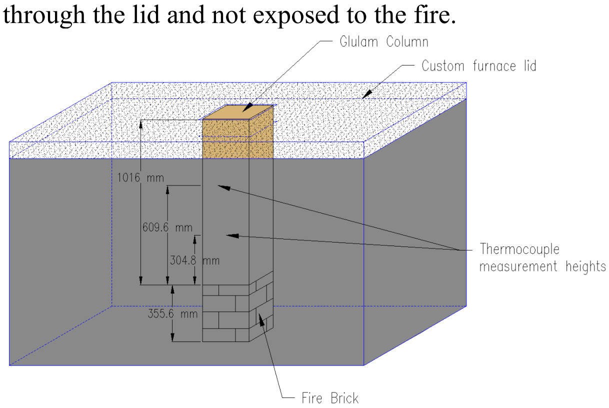

Figure 2: *Schematic of furnace with glulam column and custom lid*

2.3.2 Test Termination

While the standard time-temperature curve from ASTM was followed, the termination criteria were not adhered to. Each test was terminated at 180 minutes in order to obtain the char depth at this time. To terminate the tests, the gas to the furnace was turned off and the specimen was removed from the furnace using a lifting plate that was attached to the top of the of the column and connected to a hoist.

As the column was lifted out of the furnace, a fiberglass blanket was draped around it to smother the flames. The blanket was used until the column was safely away from the furnace and water could be applied. The removal procedure was less than 1 minute in duration before water was applied and, once extinguished, the char layer was removed to ensure smoldering did not continue and enable residual wood measurements (Figure 3).

Figure 3: *Glulam column after 180-minute exposure to the standard fire (left) and with the char layer removed (right).*

3 RESULTS

The thermocouples allowed the char front to be tracked, by using the 300˚C isotherm [9]. The temperature data collected during the second test is illustrated in Figure 4 with the ASTM E119 standard fire curve provided for reference. The alpha character identifies each face of the column and the numbers indicate the depth (in mm) of the thermocouple from the fire-exposed face. The average of the upper and lower thermocouples for each face are presented. Additionally, after the specimens cooled, they were sawn and visual measurements of char depth were taken as a second method to verify the char depth.

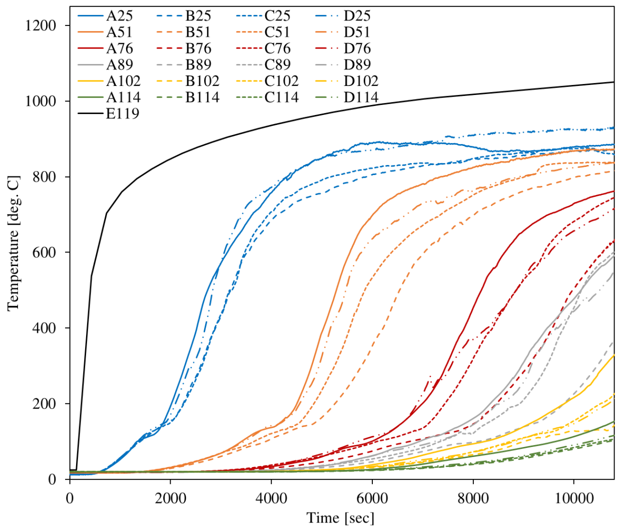

Figure 4: *Thermocouple Data from a Douglas-fir glulam column.*

3.1 Isotherm Results

A summary of the mean times at which thermocouples at different depths reached 300°C can be found in Table 1. The mean times were calculated by first averaging the times for thermocouples at a given depth for one specimen and then averaging those times for all three specimens.

Table 1: *Average times to reach 300°C at each depth.*

TC Depth (mm)	Mean time [min.]	Mean minimum time [min.]	Mean maximum time [min.]
25.4	39	34	47
50.8	86	75	98
76.2	136	108	153
88.9	162	129	181

For glulam components, the char rate generally used for calculations in the United States and Canada is nominally 0.635 mm/min, which is based on 1-D charring. Using the 300°C isotherm, the measured linear charring rates at each depth for each column are provided in Table 2. These char rates show the impact of the char layer that forms, decreasing the char rate from an average of 0.68 mm/min at 25.4 mm to an average of 0.55 mm/min at 88.9 mm.

Table 2: *Linear char rate at each depth.*

TC Depth (mm)	Linear Char Rate (mm/min.)		
	Column 1	Column 2	Column 3
25.4	0.65	0.67	0.71
50.8	0.59	0.61	0.60
76.2	0.54	0.57	0.58
88.9	0.52	0.56	0.56

3.2 Residual Cross Section Results

While the linear char rates at each depth provide insight into the char rate behaviour at fixed depths, they do not provide the char rate at a specific time. This is because the locations of the thermocouples are static, and the char front often falls between thermocouple depths. To determine the char front location at a specific time, such as 180 minutes, the exposure must be stopped at that time and the char front spatially measured. To accurately make these measurements, after testing was completed, the columns were cross sectioned approximately every 150 mm. Each cross-section was imaged with a desktop photo scanner at a resolution of 300 ppi, converted to 8-bit grayscale, and then converted to a binary image that excluded the background and charred black wood. The binary images were analysed using various algorithms to detect the wood/char boundary and exclude other shapes. These images include the portion of wood that would be pre-heated and considered the zero-strength layer during testing. This produced a clean binary image that can then be easily measured. During this process the location of the original centre of the column as well as the scale were maintained. An example of this progression of image analysis is shown in Figure 5.

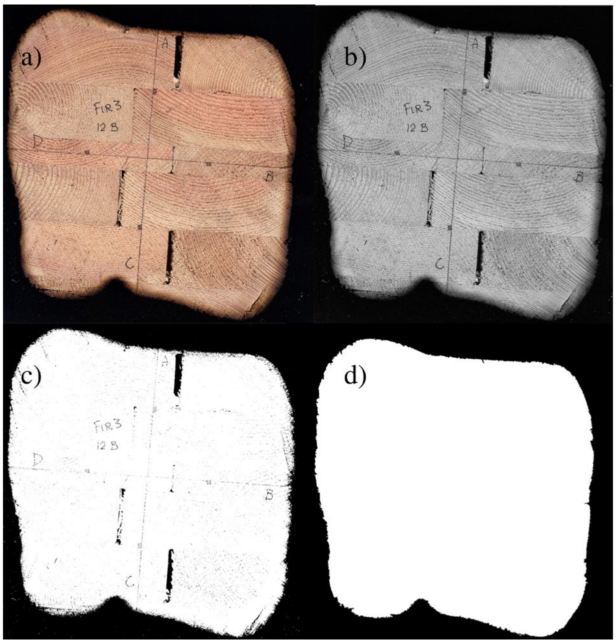

Figure 5: *Cross section imaging of Column 3 at 300 mm from bottom. a) Original cross section. b) Aligned, 8-bit grayscale image. c) Threshold value applied to exclude background and char. d) Cleaned image leaving only wood to char boundary.*

To avoid the effects of rounding at the corners, measurements from the original column centre to the char boundary were taken along the middle 76 mm of each column face. This method includes any effects from voids at internal seams that accelerated the char rate in some places as observed on the lower face of the column in Figure 5. Therefore, columns without internal voids may have a slower measured char rate. The char depth measurements were then averaged across each column and can be found in Table 3. The average measured char depth for all three specimens was 98.5 mm, resulting in a linear char rate of 0.55 mm/min at 180 minutes.

Table 3: *Average char depths for each column.*

Column No.	180-minute Char Depth [mm]	Minimum Char Depth [mm]	Maximum Char Depth [mm]
1	96	83	123
2	99	83	133
3	101	76	138

4 DISCUSSION

Since the times in Table 1 are from 1D charring at the face of the column, they may be compared to times calculated using the current model used in the United States [7]. Currently, the char depth at a given time up to 120 minutes may be calculated using Equation 1 below. Equivalently, the exposure time may be calculated given a specified depth by using Equation 2.

$$a_{char} = \beta t^{0.813} \quad (1)$$

$$t = \left(\frac{a_{char}}{\beta_t}\right)^{1.23} \quad (2)$$

Where a_{char} is the char depth in mm and β_t is the nominal char rate in mm/min$^{0.813}$ and t is the exposure time in minutes.

To account for reduced strength in the areas of the wood that are heated but not yet charred as well as rounding at the corners, the effective char depth (a_{eff}) is estimated to be 20% greater than a_{char}. This results in a more conservative model shown in Equations 3 and 4 that are used for residual strength calculations.

$$a_{eff} = 1.2 \times \beta_t t^{0.813} \quad (3)$$

$$t = \left(\frac{a_{char}}{1.2\beta_t}\right)^{1.23} \quad (4)$$

Figure 6 shows the averaged data in Table 1 plotted with the models from Equations 2 and 4. The model from Equation 2 fits the data well at lower depths and times but it under-represents the char rate at higher times and depths. While the model in Equation 4 overestimates the time to reach a char depth of 88.9 mm by 20 minutes, further analysis on the effects of rounding and the pre-heated layer must be completed to verify if Equation 4 is conservative.

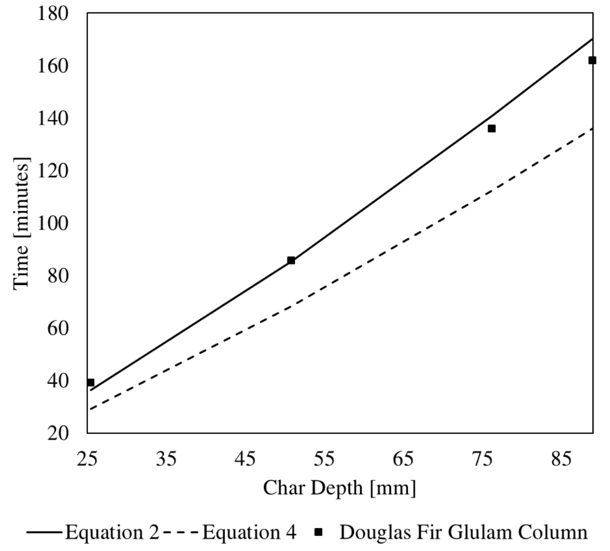

Figure 6: *Average measured time to char (300°C) to different depths compared with the models described in Equations 2 and 4.*

Like the 300°C isotherm results, the model from Equation 1 under-predicts the char depth slightly, while the model with the 20% factor in Equation 3 is found to predict deeper char formation by 9 mm or more (Figure 7).

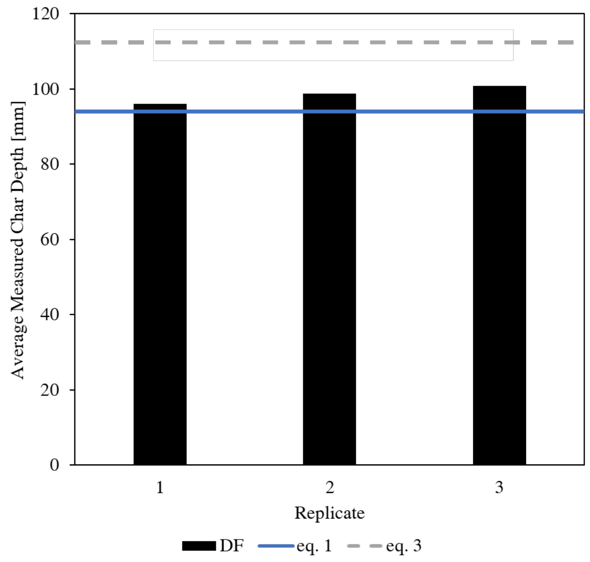

Figure 7: *Measured char depths versus depths predicted from Equations 1 and 3.*

The data from the residual char depth measurements can be combined with the 300°C isotherm measurements to cover the full extent of the 180-minute exposure, as shown in Figure 8. From Figure 8, it appears that the existing char rate model using the nominal char rate of 0.635 mm/min is appropriate for the glulam columns at one and 120 minutes. However, the measured data deviates from the model at higher temperatures and times with the measured char depth at 180 minutes slightly more than predicted by Equation 2. Because of this deviation, a model that better fits the measured data is suggested in Equation 5. This model was developed by modifying the exponential factor in Equation 1 to fit the measured data and is included in Figure 8.

$$a_{char,3hr} = \beta_t t^{0.868} \tag{5}$$

Similar to the current model, Equation 5 could be made more conservative to account for corner rounding and reductions in strength and stiffness by including a 20% factor.

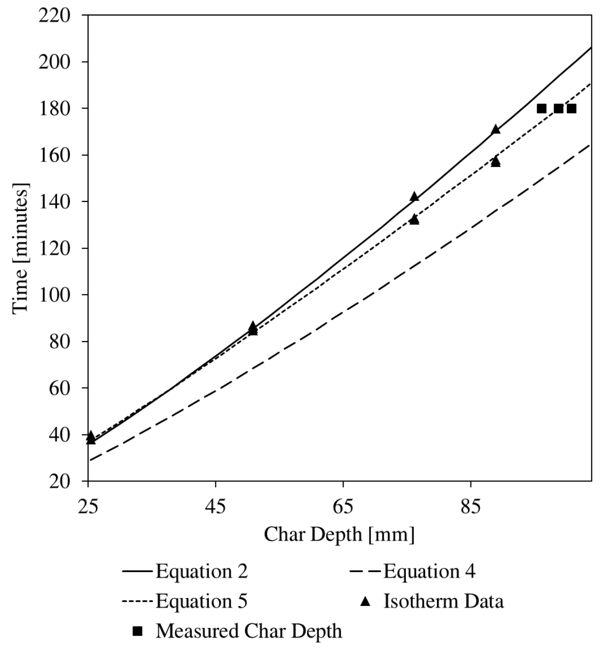

Figure 8: *Data from the 300°C Isotherm combined with data from the residual cross sections compared with 3 models.*

Future work will evaluate the thickness of the pre-heated zone below the char layer and the structural eccentricities will be assessed from the remaining cross-section images. This work will verify if the current reduced cross-section method is applicable at 180 minutes. Additional work to further validate the model presented in Equation 5 will also be undertaken via comparison with additional glulam columns.

5 CONCLUSIONS

Current char depth and char rate models for exposed glulam columns have been validated for up to 120 minutes of standard fire exposure. However, recent changes to the building codes permitting tall timber buildings has increased the desire to expose wood members with higher required fire resistance ratings. To date, no 180-minute tests on exposed glulam had been conducted. To determine if the current models were suitable at 180 minutes, three glulam columns were tested. The results of these tests may be used to carry out an engineering analysis on glulam columns to be exposed and to be fire resistance rated up to 180 minutes.

The results found the overall linear char rate for the three columns based on the measured char depth was 0.55

mm/min for 180 minutes. This is slightly slower than the current nominal char rate used of 0.635 mm/min, which is limited to 120 minutes. Additionally, the current, non-linear model underestimated the char depth at 180 minutes while the model with a 20% factor overestimated the char depth.

The effects of loading on char depths and the char rate were not tested in this study and would require further study.

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REFERENCES

[1] T. T. Lie, "A method for assessing the fire resistance of laminated timber beams and columns," *Canadian Journal of Civil Engineering,* vol. 4, pp. 161-169, 1977.

[2] R. H. White and E. V. Nordheim, "Charring rate of wood for ASTM E 119 exposure," *Fire Technology,* vol. 28, pp. 5-30, 1992.

[3] ASTM, "ASTM E119 Standard test methods for fire tests of building construction and materials," ed. West Conshohocken, PA: ASTM International, 2018.

[4] A. Counsil, "National Design Specification for Wood Construction," *Leesburg VA USA,* 2005.

[5] J. Schmid, A. Just, M. Klippel, and M. Fragiacomo, "The reduced cross-section method for evaluation of the fire resistance of timber members: discussion and determination of the zero-strength layer," *Fire Technology,* vol. 51, pp. 1285-1309, 2015.

[6] S. Breneman, M. Timmers, and R. Dennis, "Tall Wood Buildings in the 2021 IBC Up to 18 Stories of Mass Timber," ed. www.woodworks.org: WoodWorks, 2019.

[7] "Calculating the Fire Resistance of Wood Members and Assemblies, Technical Report No. 10," American Wood Council, Leesburg, VA2018.

[8] R. H. White, "Fire resistance of exposed wood members," in *Wood & fire safety: proceedings, 5th international scientific conference, April 18-22, 2004... Slovak Republic.[Svolen, Slovakia]: Faculty of Wood Sciences and Technology, Technical University of Zvolen, 2004: Pages 337-344.*, 2004.

[9] E. L. Schaffer, *Review of information related to the charring rate of wood* vol. 145: Forest Products Laboratory, 1966.